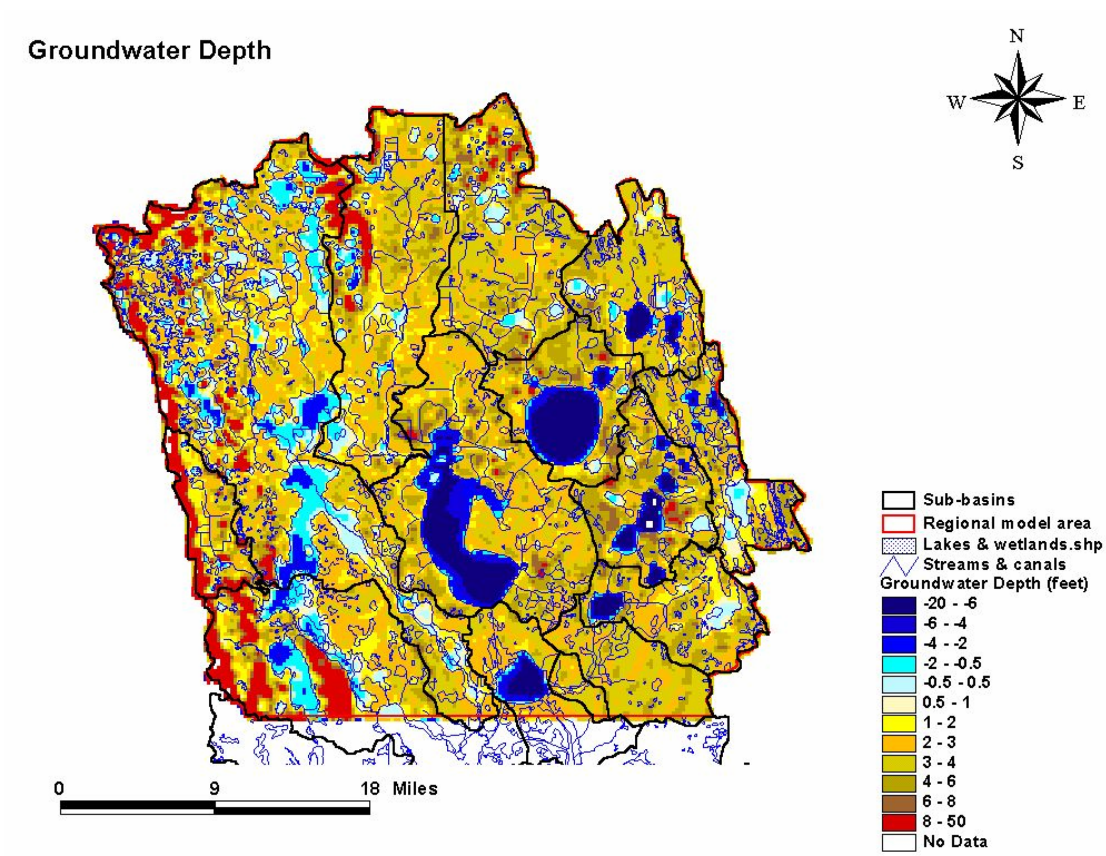
KISSIMMEE RIVER BASIN MODEL SELECTION

Request for Additional Information on MIKE SHE



2005-04-18

Model Selection for the Upper Kissimmee study

April 2005

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☐ Open

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☐ Proprietary

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EarthTech	Ed Kent	
University of Miami	Fernando Miralles-Wilhelm	

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1 THE SELECTED WATERSHED MODELING TOOL MUST HAVE THE ABILITY TO EXPORT, TO ASCII OUTPUT, ALL TIME SERIES DATA FOR EACH ELEMENT AT ALL LOCATIONS WITHIN THE MODEL. PLEASE DISCUSS THE ABILITY OF YOUR MODELING TOOL TO EXPORT THESE DATA.

MIKE SHE allows that input data are specified in different formats including .shp files (ArcView/ArcGIS), simple XYZ ascii files or in DHI´s dfs2 grid file format (see Figure 1)

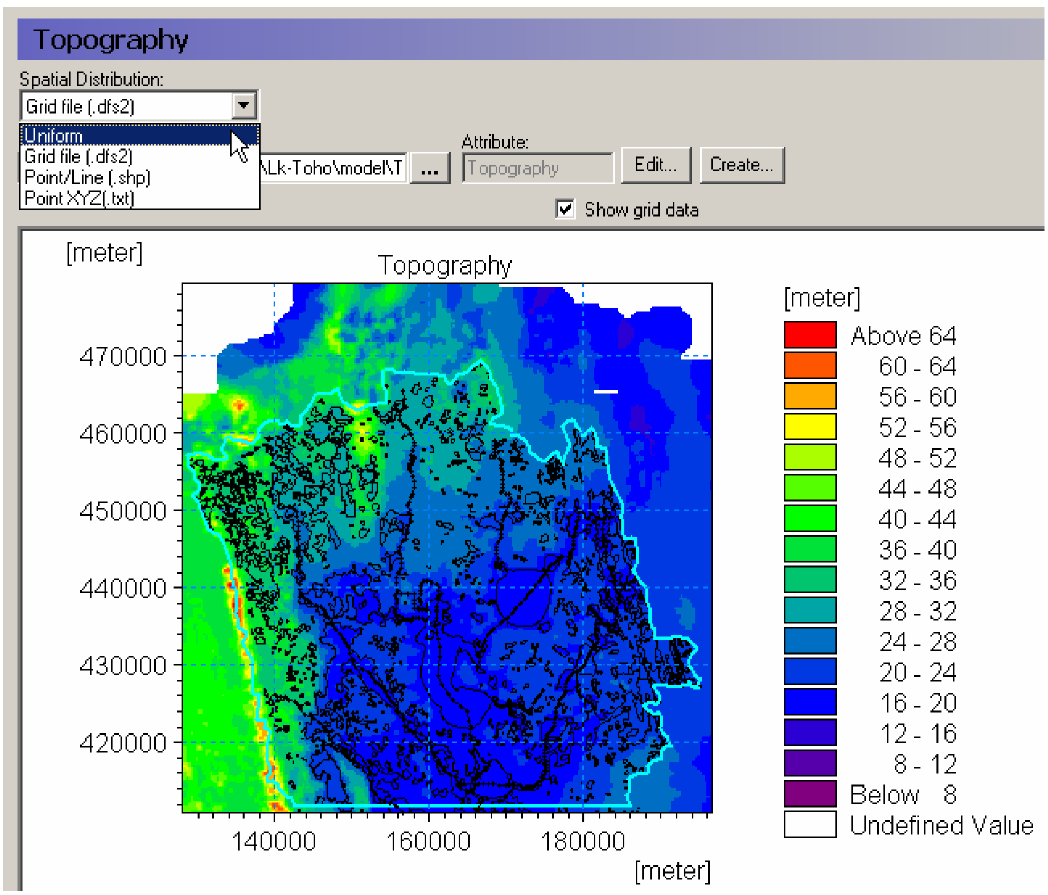


Figure 1 Supported input formats for spatial data.

Input data can be provided in any of these formats and in any grid size. When running MIKE SHE´s pre-processor the input data will all be transferred to the grid-size specified in the model. Processed input data can be exported to ASCII, shp or grid-file formats (including surfer grids).

Results (maps or time-series) can be exported to ASCII grid / time-series formats using the grid editor and/or the results viewer as illustrated in Figure 2

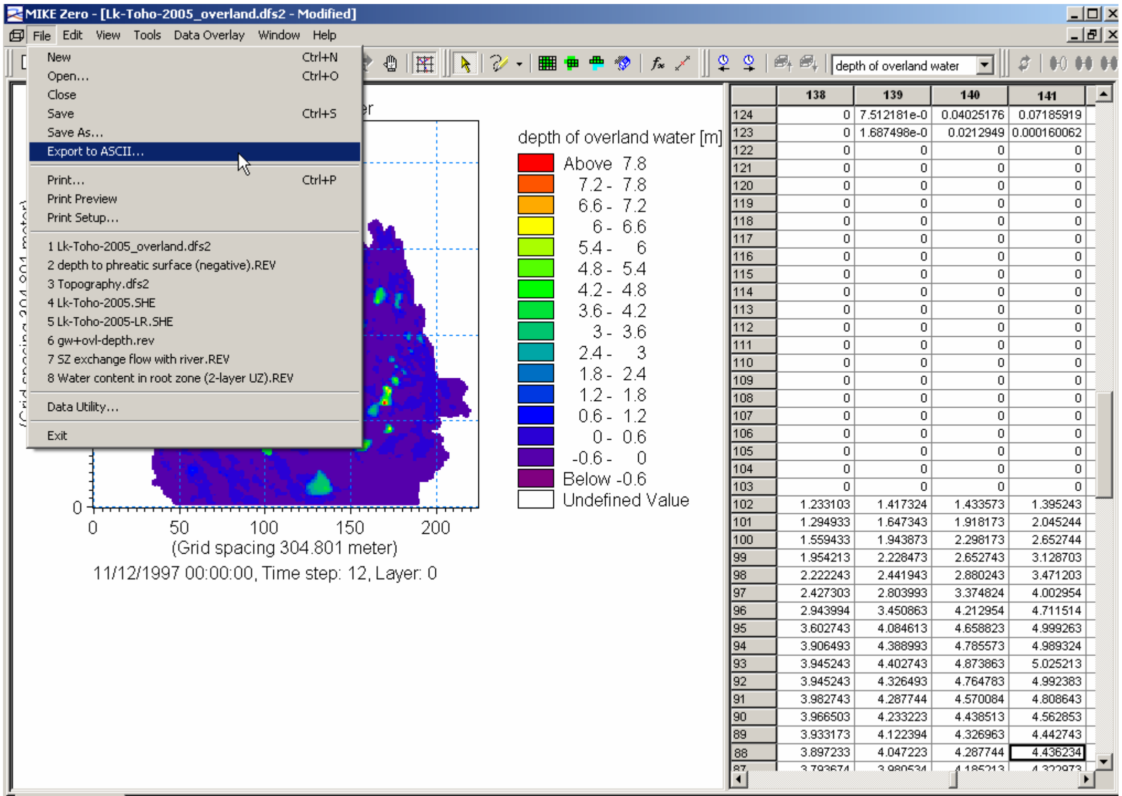


Figure 2 Exporting of grid data to ASCII files.

If statistical data are required, MIKE SHE includes tools to calculate and create map based output files for the mean, minimum, and maximum values. The calculated statistics can subsequently be exported to ASCII grid files.

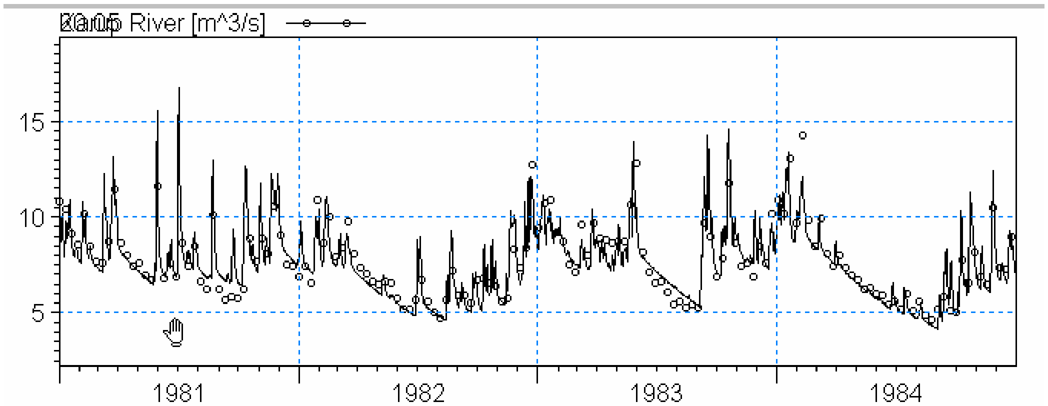
All DHI tools allow cut-and-paste from the built-in spreadsheet functionality (see Figure 2) to EXCEL.

If the SFWMD (the District) desires to produce certain output maps, for instance hydro-period maps, in an automated manner, it is recommended that a special tool be built for that purpose. DHI offers a number of library functions that enable easy reading and writing of DHI files; therefore, special programming tools can be easily developed. Such a tool could be created by programmers outside of DHI, but a DHI programmer could develop such a tool in less than 1 man-day.

2 THE SFWMD HAS INVESTED A GREAT DEAL OF EFFORT COLLECTING DISCHARGE DATA FOR EACH WATER CONTROL UNIT WITHIN THE KB. THESE DATA WILL BE AVAILABLE DURING CALIBRATION/VERIFICATION EFFORTS. DESCRIBE HOW THE MODEL CAN UTILIZE THESE DATA TO EVALUATE THE PERFORMANCE OF THE SIMULATION FOR EACH WATER CONTROL UNIT WITHIN THE KB.

Together with groundwater head data, discharge data are the primary calibration and validation targets for the model. Discharge data are essential in order to ensure that the model produces a proper water balance for the individual water control units and to demonstrate that the model responds correctly to rainfall and other stresses. The MIKE SHE model will be calibrated against all discharge time-series available in order to ensure that individual basins produces proper runoff hydrographs.

In a system as heavily controlled as the Kissimmee River basin, simulation of discharges is not an easy task. For most uncontrolled (natural) basins, with detailed rainfall data coverage, discharges can normally be produced rather precisely by both lumped rainfall-runoff models and by more sophisticated distributed models like MIKE SHE. An example of a calibrated discharge hydrograph simulated with MIKE SHE in a natural catchment is shown in Figure 3.



ME=0.0584587
MAE=0.591362
RMSE=0.823139
STDres=0.821061
R(Correlation)=0.902816
R2(Nash_Sutcliffe)=0.812421

Figure 3 Example of MIKE SHE simulation of an observed runoff hydrograph from a natural basin with good rainfall data.

In heavily controlled systems like in Florida, simulation of runoff hydrographs is a substantially more complicated matter. Also the fact that large runoff volumes are often associated with a few large storm events, makes simulation of discharge more difficult. If a single storm event is not properly captured in the available rainfall data then the cumulated runoff for the entire season may already be off by 10-20 percent due to a single large storm event.

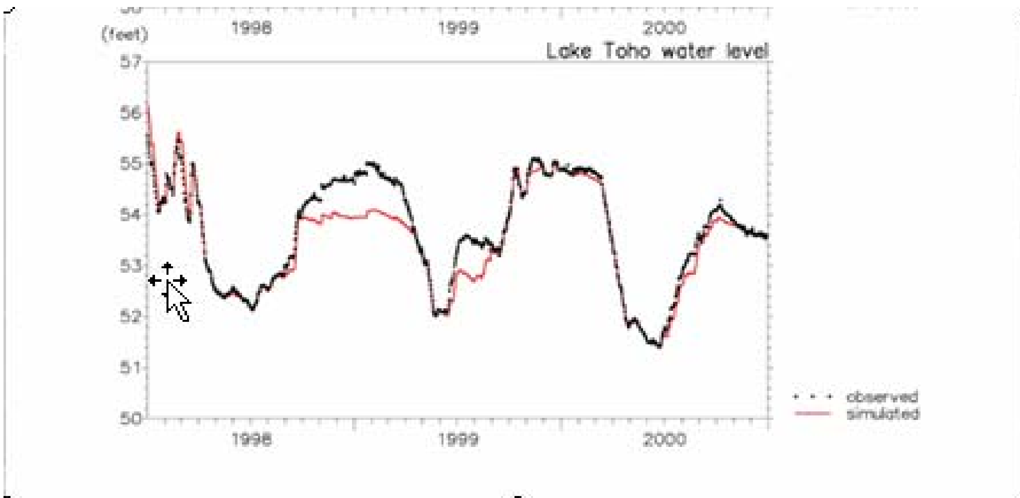
In Florida, DHI has previously used an approach where model calibration has involved an attempt to meet the observed water level upstream of a control structure (eg. a lake water level) and the observed runoff hydrograph through the control structure. MIKE11´s structure operation module was operated in a simple manner in order to maintain the observed head water level with the simple operation algorithm:

If (WL_simulated) > (WL_observed) then open gate;
Else close gate.

Gate opening and closing is done simply using the allowed gate lift speed on the relevant structure (eg. 1 cm/sec). This gate operation in MIKE11 is done on each single modeling time-step (eg. 5-30 minutes time-steps). In cases where there is too much water (inflows) to the lakes then this gate operation would result in a good match on the lake water levels but in too much runoff (as long as the simulated discharge does not exceed the capacity of the gate). The challenge is to meet the Lake water levels and the observed runoff simultaneously. If the model can do that then you can be pretty sure that you have a good model.

As an example, Figure 4 shows calibrated water level and runoff in Lake Toho and at the S-61 structure (Lake Toho outlet gate) in the existing MIKE SHE Upper Kissimmee Basin model. During the wet season of 1998 there is a perfect match of the observed water level but the runoff is too high. In the dry season of 1998/1999, the observed water levels are never reached by the model because the simulated inflows are too small. The simulation of the dry season lake water levels is a complicated matter because a perfect match requires a perfect representation of rainfall, actual ET and basin runoff as well as a perfect model description of the storage-volume relations in the lake. That is obviously not a simple task. In 1999 and 2000 there is a pretty good simulation of both stage and discharge, which you can only do if you have a model that realistically represents the basin hydrology.

Thus discharges will be used in combination with surface water and groundwater levels as the primary calibration targets. We will incorporate and calibrate the model against all available discharge measurements within the project area.



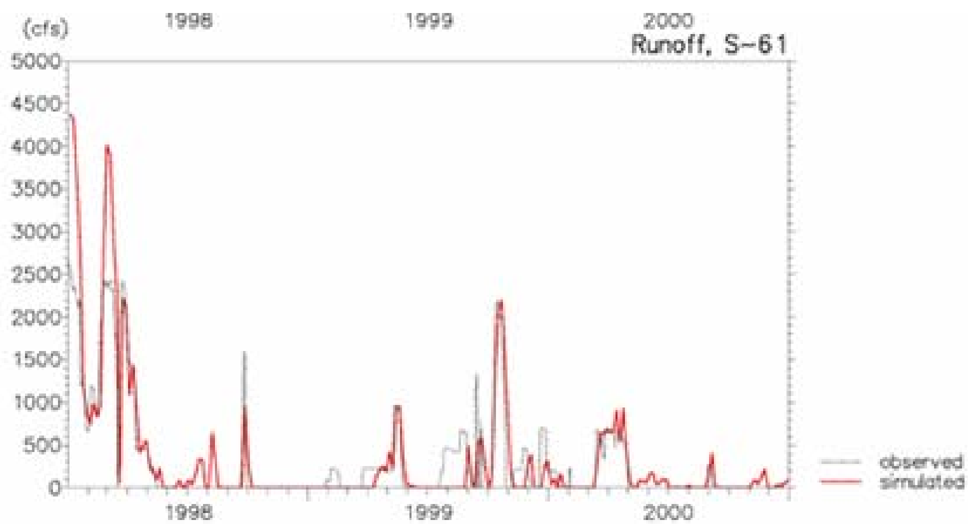


Figure 4 Calibrated stage in Lake Toho and runoff at S-61.

3 PLEASE DESCRIBE THE ABILITY OF THE HYDRODYNAMIC EQUATIONS WITHIN YOUR TOOL TO ADDRESS DEPTH-VARYING ROUGHNESS FOR OVERLAND AND CHANNEL FLOW.

3.1 Channel Flow Roughness

Depth-varying roughness in the hydrodynamic equations can be dealt with in three ways, and this is done within the cross section editor of MIKE 11. Here the roughness is specified as the Manning's 'n' or the inverse 'M' according to the user's preference. The user has 3 choices for working with the depth-variation of the roughness:

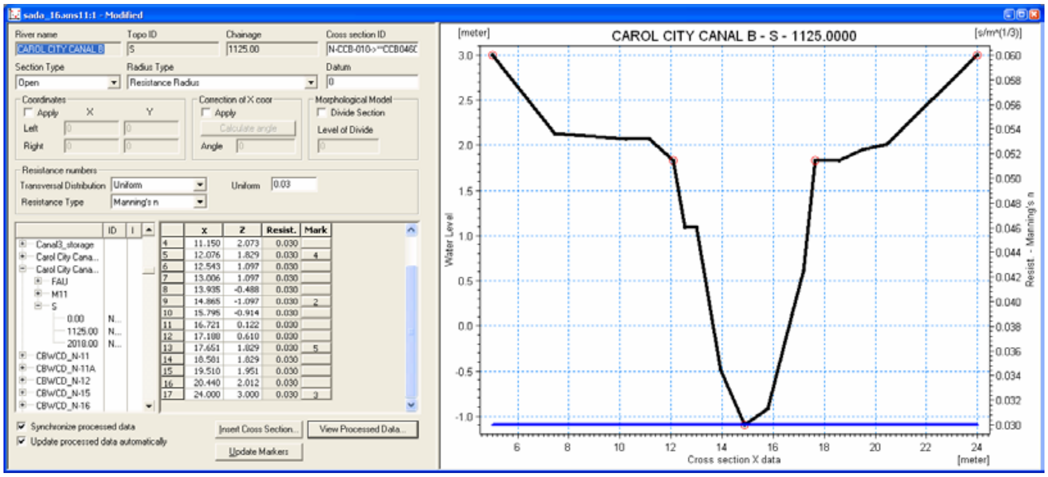


Figure 5 Cross-section with uniform roughness

Figure 5 shows the MIKE11 cross section editor when a *uniform roughness* is assigned throughout the cross section, i.e. there is no depth variation of the roughness.

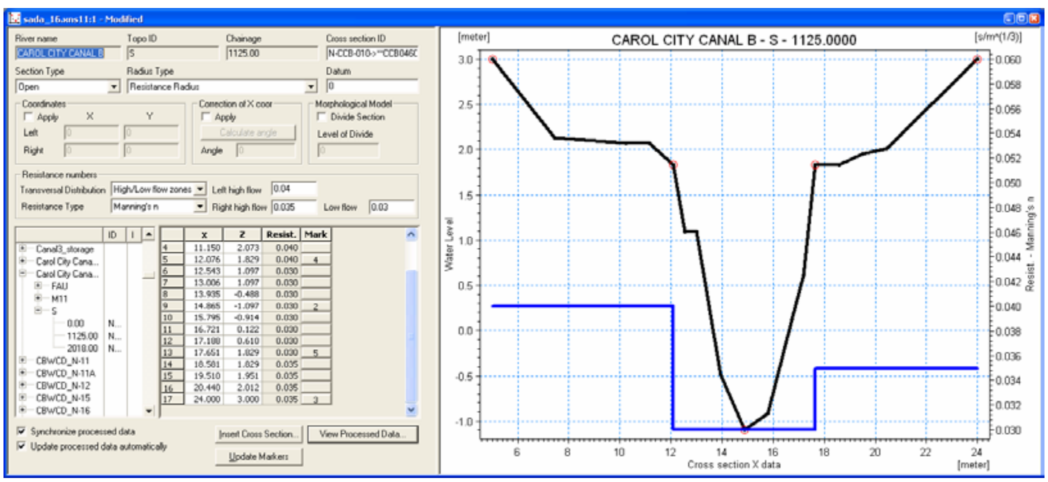


Figure 6 Cross-section with three roughness zones

Figure 6 shows a screen dump of MIKE11's cross section editor when *three roughness values* are assigned to three zones in the cross section typically referred to as the low flow section, left high flow section and right high flow section. The black line is the cross section and the blue line is the roughness variation across.

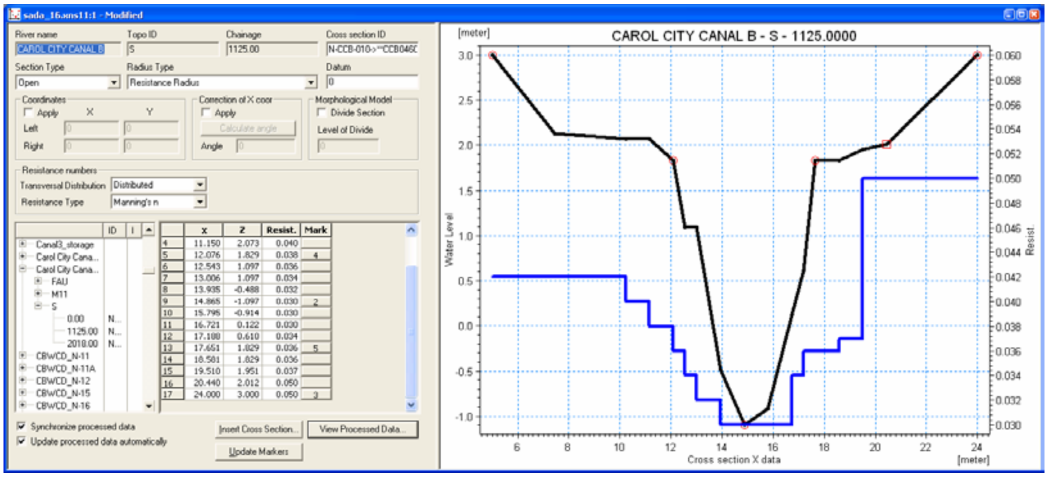


Figure 7 Cross-section with fully distributed roughness.

Figure 7 shows a screen dump of MIKE11´s cross-section editor when fully *distributed roughness values* are applied; i.e. for each segment between two X, Z data sets a specific roughness value applies.

The choice between uniform, three-zone based and distributed roughness can be made cross-section by cross-section. Once the user has specified/changed the cross-section data and the roughness variation across the section, MIKE 11 automatically calculates the so-called processed data in each cross section. This is a table of water levels and corresponding cross section area, radius, width and roughness. This tabulated relation between water level and roughness is how depth-varying roughness is applied in the hydrodynamic equation in MIKE 11. The processed data table, and graphics showing the depth-variation of the above cross section with distributed roughness, is shown in Figure 8.

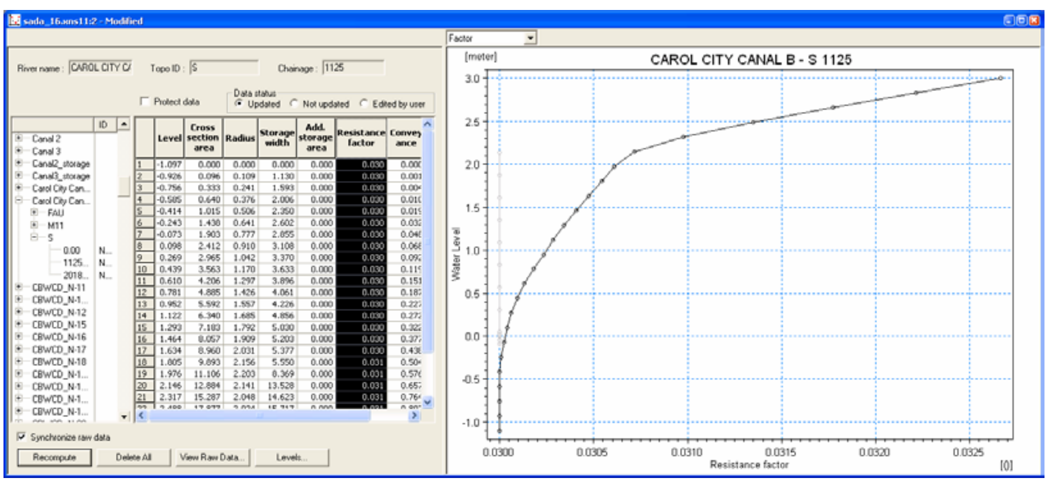


Figure 8 Processed cross-section data in MIKE11´s cross-section editor.

3.2 Overland Flow

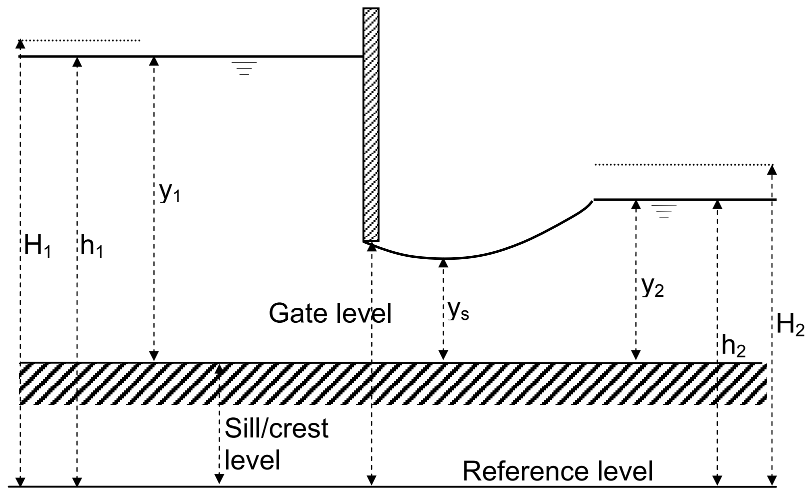
In the overland flow module, MIKE SHE currently does not support variations of the Manning´s value as a function of flow depth. This development is planned for inclusion in the MIKE SHE version later in 2005. However, in our experience this is not a very important feature for most large scale overland flow problems and MIKE SHE has been successfully calibrated and applied to many projects throughout the world, including Florida, without the depth varying roughness. If, however, it is deemed necessary to include the depth varying roughness within this project, we will immediately include it in the present version of MIKE SHE. Total development time for this feature would be 1-2 man-days. It should; however, be emphasized that a model should be kept as simple as possible. Hence, application of a depth varying overland roughness coefficient should be of importance for the hydrological behavior of the basin, and field data should be available for process documentation and model calibration.

4 PLEASE DESCRIBE THE ABILITY OF YOUR MODEL TO HANDLE THE FLOOD EVENT ROUTING ISSUES IN THE FOUR PRIMARY FLOW REGIMES DESCRIBED IN ATTACHMENT 1. YOUR DESCRIPTION SHOULD INCLUDE FLOW CHARTS AND GRAPHICS DEMONSTRATING HOW THE TOOL DOES OR WILL ADDRESS THESE CONDITIONS.

A vertical lift gate in MIKE 11 is defined by the following parameters:

- *Location*: The river name and chainage (also known as river mile or river station) at the location of the gate
- *Number of gates*: If two or more gates at the same location have the same geometry and have fully synchronized operation, the number of identical gates can be specified.
- *Gate width*: The gate opening is assumed to rectangular with constant width.
- *Sill/crest level*: Elevation of the sill/crest that the gate closes against.
- *Max rate*: The maximum rate at which the gate can change. The rate of any gate change dictated by the operational rules will be limited by the specified max rate change.
- *Hydraulic parameters*: The equations used to calculate the four flow regimes requires a number of parameters such as loss coefficients and the under flow contraction coefficient to be specified.
- *Operational rules*: At each time step in the simulation MIKE 11 needs to decide about the gate level (the elevation of the gate = sill/crest level + gate opening) as defined by the operational rules. The options and features available for defining operational rules in MIKE 11 are explained in details in the reply to question (8).

The flow through a vertical lift gate, which in MIKE 11 is called an underflow gate, is calculated such that each of the four flow regimes are taken into account. At each time step in the simulation MIKE 11 will individually for each vertical lift gate decide which of the four flow regimes that applies. Given the following definition sketch (see Figure 9), which shows a vertical lift gate in the controlled-free flow regime, this is done as described in the following:



y : Water depth
h : Water level (water surface elevation)
H : Energy level

Figure 9 Definition sketch for vertical lift gates in MIKE11.

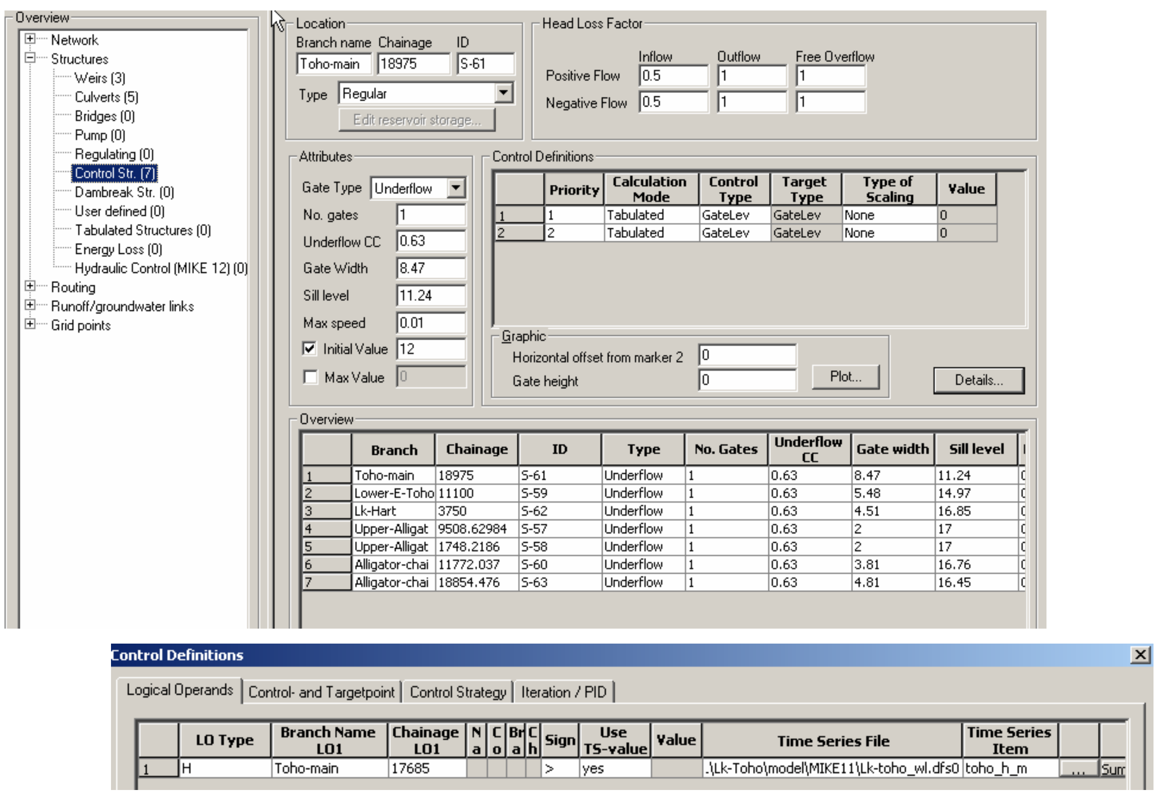


Figure 10 Main input dialog for MIKE11´s control structure module.

Figure 10 shows a screen dump of the control-structure specification in MIKE11´s GUI. The upper screen dump illustrates the main input specification for S-61 which is mainly gate geometry. The bottom screen dump shows the conditions (logical expression) associated with priority 1 for S-61. For this simple case the condition is simply that if the simulated water level at Toho-main, mileage 17685 m (which is in Lake Toho) is higher than the observed water level in Lake Toho, then the gate should open to it´s maximum opening using he maximum allowed opening speed. This was the control algorithm used for the calibration period of the Upper Kissimmee model. For scenarios the observed water levels was simply exchanged with a time-series of the projected operation schedule (water level target) for Lake Toho. This is a very simple control algorithm but any control stragegy can be implemented using a series of conditions (logical expressions) with associated control strategies. In the example above, if priority 1 is not fulfilled, then priority 2 would be used which would simply close the gate. There are no limit to the number of priorities that may be added in MIKE11.

4.1 Controlled flow regime (A and B)

If the upstream water level (h_1) is higher than the gate level, the presence of the gate will force the passing water into a jet which may cause the formation of supercritical flow in the region of the issuing jet. Should this occur in a channel with a high tail water level, a hydraulic jump may occur downstream of the gate. In either case, the discharge through the gate will be a function of the gate geometry and upstream water level only, i.e. flow regime A.

As the tail water rises, the hydraulic jump moves upstream, towards the gate. When the jump reaches the gate, it will drown the supercritical jet, the water level at this point will suddenly rise to the tail water depth and the flow regime will be B. This change in the flow at this instant is discontinuous, due to the discontinuous nature of the hydraulic jump itself. At the point of change over, the discharge will suddenly decrease.

The choice between flow regime A and B is done by comparing the downstream water depth with the minimum water depth at which the hydraulic jump is submerged ($h_{2,}$ min):

$$y_{2,\min} = \frac{1}{2} y_s \left(\sqrt{1 - 8F^2} - 1 \right)$$

If the flow regime is A, the energy equation is applied between the point upstream of the structure and the point with minimum water depth downstream of the gate, to yield the free discharge through the gate. Assuming, as in most cases, a zero inflow head loss, it can be shown that this assumption is equivalent to the generally accepted form of the vertical sluice equation viz:

$$Q_A = C_d w y_g \sqrt{2 g y_1}$$

Where w is the gate width, y_g is the gate opening and C_d is:

$$C_d = \frac{C_c}{\sqrt{1 + C_c \frac{y_g}{y_1}}}$$

If the flow regime is B the submerged orifice equation is applied:

$$Q_B = \mu C_d w y_g \sqrt{2g(h_1 - h_2)}$$

4.2 Uncontrolled flow regimes (C and D)

The gate will only have a controlling influence on the flow if the gate level is lower than the upstream water level (h_{US}). If this is not the case, the discharge will be calculated assuming an overflow structure. For overflow structures the first assumption is that the flow is free and the flow as function of the upstream water level is calculated (Q_C). Secondly, if the water level at the crest (h_{Crest}) is larger than the downstream energy head (H_{DS}) then free flow is assumed. Otherwise, a calculation of submerged flow (Q_D) is done, and the final choice between uncontrolled free flow regime (C) and uncontrolled submerged flow regime (D) is done by choosing the regime with the smallest flow. Q_C and Q_D are both calculated by using the energy equation. For flow regime C this is done between the upstream cross section and the crest taking the energy loss due to the flow contraction into account. For flow regime D this is done between the upstream cross section and the downstream cross section taking the energy loss due to the flow contraction upstream and flow expansion downstream into account.

The following flow diagram summarizes how MIKE 11 selects the appropriate flow regime for a vertical lift gate.

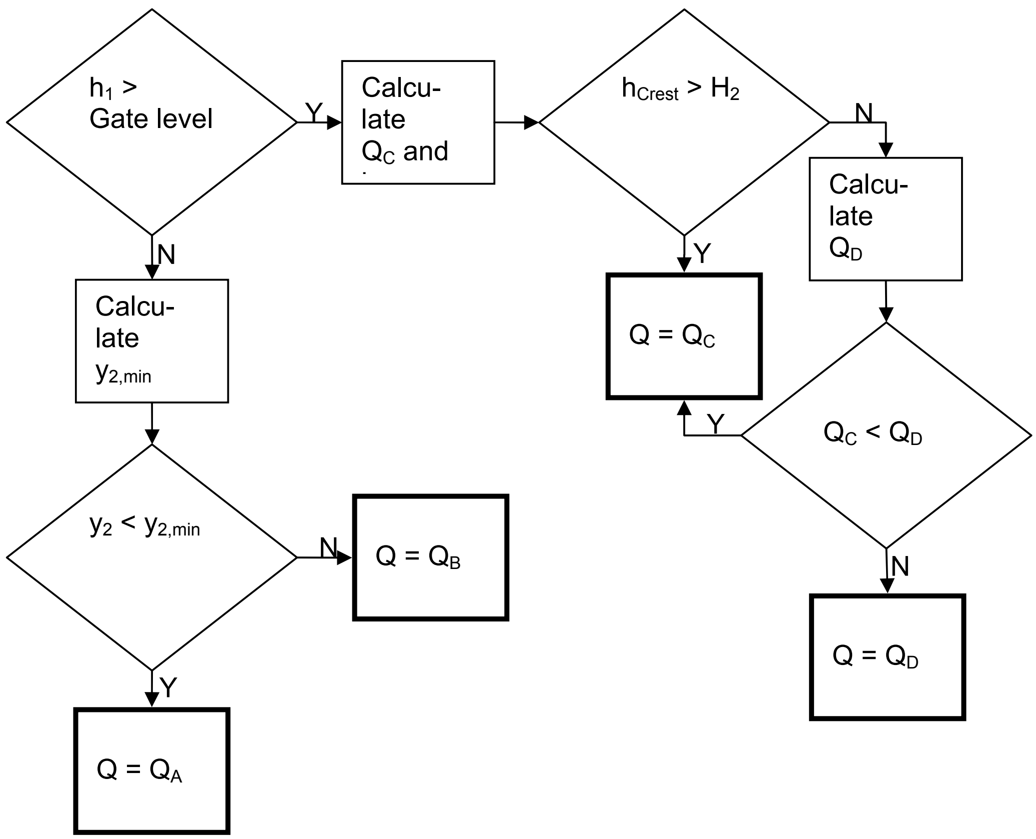


Figure 11 Flow chart used by MIKE11 to evaluate the four flow regimes.

4.3 Using Flow tables (Q-h relations) for structure operations

MIKE11 is the only of the short listed software systems that includes a real structure operation module. All other codes use Q-h relations to describe the flow across hydraulic control structures. As long as these structures are fixed (i.e. no operations) this approach is manageable, although relatively cumbersome because Q-h relations must be derived and entered in a tabular form, while MIKE11 would just require structure geometry. In principle Q-h relations may also be used to describe lift-gates. Seen in the light of the large number of control structures and the complex operation schedules then using Q-h relations, in practice, becomes very difficult.

As described above MIKE 11 automatically evaluates the flow regime at each time step as a function of 1) upstream water level 2) downstream water level and 3) gate opening/level. Using pre-calculated flow tables (Q-h relations) is possible in theory. However, as the flow is dependent on the three mentioned variables a pre-calculated table would not be a simple Q/h table, but a large 3-dimensional table from where the flow could be looked-up or interpolated with given h_1, h_2 and y_g. For each of the three variables the table entries would typically be defined by a range (min/max) within which the entries are defined at equidistant intervals. The min/max range would have be wide enough to cover any foreseeable value of water level or gate opening, and the intervals would have to be small enough to pick up the discontinuous or very sudden changes in the flow for instance occurring when the down stream water level increases and suddenly makes the flow change from free to submerged. The number of entries required for each variable could easily be 25-50. With three variables the number of pre-calculated flow values in each table would be between 15.625 and 125.000 (25^3 and 50^3) which might lead to table sizes that are difficult to manage. In other words, generating the flow tables and deciding about the range and intervals would be a compromise between manageable table sizes on one side and simulation accuracy on the other side. Even if accuracy is compromised to obtain manageable table sizes it would still be a very large effort to derive and enter these large tables manually in text files.

5 PLEASE PROVIDE AN ITEMIZED LIST OF CALCULATION OPTIONS FOR SIMULATION OF INFILTRATION, AND A BRIEF NARRATIVE EXPLAINING EACH OF THE ALGORITHM OPTIONS. IN PARTICULAR, WE WOULD LIKE TO UNDERSTAND WHAT SIMPLIFYING OPTIONS ARE AVAILABLE.

5.1 Richard´s equation approach

The full Richard´s equation is the most comprehensive option among MIKE SHE´s unsaturated zone/infiltration models. If Richard´s equation is applied, then the infiltration calculation will be done using the actual pressure gradients in the top of the soil-profile. Hence, during a rainfall event ponding will occur on the overland. The ponding depth then acts as a pressure boundary condition for the infiltration calculation. If the soil is dry in the top of the profile very large head gradients may prevail, generating a flux which exceeds the saturated hydraulic conductivity of the soil. If the computed flux exceeds the actual ponding on the ground surface, then MIKE SHE changes the boundary condition to a flux boundary using the actual ponding depth divided by the actual time-step as a flux boundary.

DHI believes that a full Richard´s equation solution is overkill for most large-scale applications and that the cost (computational speed) far exceeds the benefit of a more correct physical representation of the soil mechanics. Based on our experience from hundreds of modeling studies throughout the world, if the main issue for the unsaturated zone model is to calculate a reasonable actual evapotranspiration and recharge rate, then a much simpler method may be applicable.

5.2 Simplified option - Gravity Flow only

The gravity flow unsaturated zone model is based on Richard´s equation but it neglects the tension/capillary forces of the soil. It is applicable in soils with limited capillary rise or in wet regimes where the capillary rise is not significant for the overall water balance. If the gravity flow routing is used, then it is assumed that the vertical pressure gradient $dh/dz = 1$. That also implies that the infiltration amount cannot exceed the saturated hydraulic conductivity. If the gravity method is used, the infiltration will equal the saturated hydraulic conductivity of the topsoil.

5.3 Simplified option - 2-layer infiltration model

In the two-layer model, an average water content of the root zone is calculated using a simple water balance approach. This method calculates actual evapotranspiration and recharge rate based on soil properties, vegetation properties (LAI and root depth), and on the actual water content in the root zone. A sample output of the actual moisture content is illustrated in Figure 12.

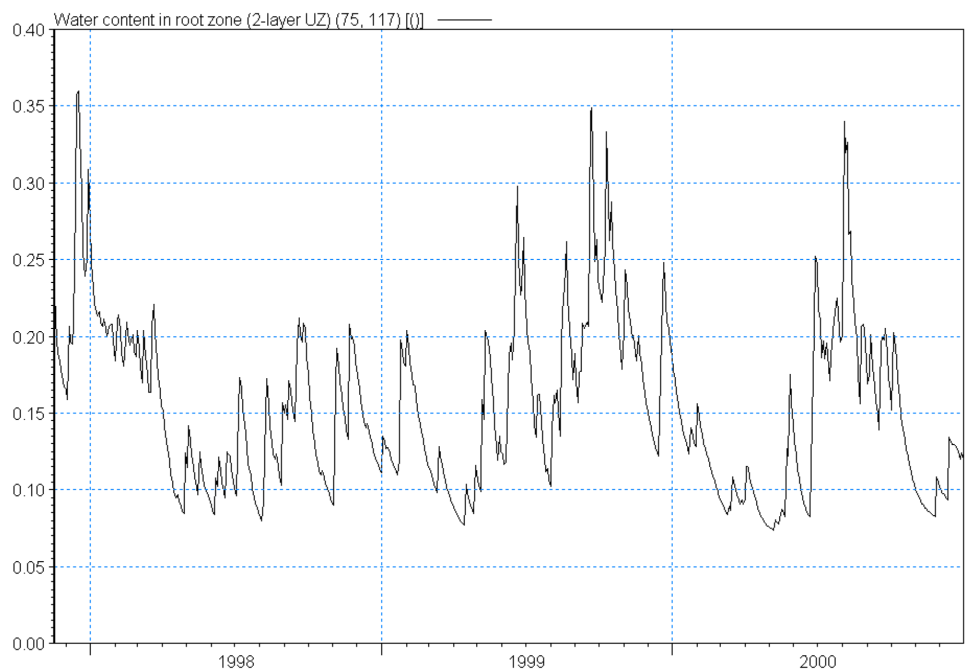


Figure 12 Sample output of the 2-layer model - average moisture content in the root zone and actual evapotranspiration at a location in the upper Kissimmee MIKE SHE model (The moisture content will always vary in between saturation and wilting point). Groundwater recharge is generated whenever the moisture content exceeds field capacity.

The simple 2-layer model does have a conceptual option that allows increased infiltration if the topsoil is dry. This is done by multiplying the saturated hydraulic conductivity (Ks) with a factor (F) calculated as a function of the actual water content:

$F = (\Theta_{FC} - \Theta_{WP}) / (\Theta - \Theta_{WP})$

Hence, for $\Theta_{ACT} < \Theta_{FC}$ the factor F is larger than 1 and thus increases the infiltration capacity of the soil. In addition the user must specify Max_F which limits the the infiltration capacity to a certain multiplier of Ks (eg. F = 10). Thus, in a conceptual manner this allows for increased infiltration capacities for dry soils.

6 APPLICATION AND DEVELOPMENT OF THE MODELING TOOL WILL REQUIRE SUPPORT FROM THE PROVIDER. PLEASE DESCRIBE YOUR COMMITMENT AND ABILITY TO MAKE SPECIFIC PERSONNEL ASSIGNMENTS THROUGHOUT THE EXECUTION OF THIS PROJECT INCLUDING SHORT TERM, HIGH INTENSITY PERIODS.

DHI is determined to utilize the total capacity of the DHI group to ensure a timely delivery at a very high scientific level. DHI´s participation in the project would naturally be managed from the Tampa office. Currently, DHI's United States personnel includes six (6) trained MIKE SHE modelers, four (4) of whom are located at the Tampa office and two (2) in DHI´s office in Portland, OR. In order to meet project demands, the Tampa office may utilize staff from other offices, including the main office in Denmark. There are approximately 25 engineers in Denmark whose primary work is MIKE SHE/MIKE11 modeling. Among those there are 4-5 engineers with good experience from various modeling jobs in Florida. These include:

- Henrik Refstrup Sørensen, who has substantial experience from various wetland oriented MIKE SHE modeling jobs in South Florida including the Upper Kissimmee basin and lots of experience from elsewhere in the world.

- Torsten V. Jacobsen, who has been involved in many of the MIKE SHE models established on the west coast of South Florida and who has substantial MIKE SHE modeling experience from similar studies throughout the world. At present, Torsten is completing a large water management study on the Okawangaa river delta, the worlds largest wetland, which has many similarities to the Everglades.

- Oluf Z. Jessen and Michael Juul Petersen, who both have worked on various MIKE SHE projects in South Florida.

Mr. Henrik R. Sørensen will, due to his particular experience with the existing model, be involved in the project as a technical advisor and supervisor. His input is particularly important in the early phase of the project where the overall modeling approach would be put together. In addition, he will be in close continuous contact with modeling staff in Florida and in Denmark and will be available in Florida at regular intervals. Finally, Mr. Sørensen will review modeling progress regularly (eg. every second week) to ensure a high scientific level of the modeling services.

The exact mix of staff has not yet been determined. However, it is anticipated that during the initial project phase, at least one (and probably two) MIKE SHE modelers will work full time on the project to meet the relatively aggressive time-schedule. Additional staff will be assigned to the project during short-term, high-intensity periods. We have not made a detailed work plan but it is anticipated that our staff will work on two tracks involving an update of the existing Upper Kissimmee model, test and implementation of revised regulation schedules (stage + discharge targets) and adjustment of the model calibration and, as track 2, construction of the lower Kissimmee model. It is anticipated that the lower model can be calibrated, at least roughly, as a separate model before the two models are merged to one model.

In addition we may define a third track, where we may assign an optimization expert to help define the most effective screening level approach. This individual would work with EarthTech and District staff to select the most appropriate screening tool in combination with one of DHI´s optimization models or a third party optimization tool.

The precise staffing mix will be chosen from the pool of modelers in Tampa and in Denmark. No matter who and where the work is done, DHI is committed to allocate whatever resources may be necessary to meet the project objectives and deadlines.

7 DURING THE CALIBRATION PERIOD OF THE MODEL, THERE ARE SIGNIFICANT STRUCTURAL CHANGES SUCH AS BACKFILLING CANALS, REMOVAL OF WATER CONTROL STRUCTURES AND CHANGES OF WATER CONTROL OPERATIONS. HOW CAN YOUR MODEL EFFICIENTLY SIMULATE THESE CHANGES WITHIN A SIMULATION?

Anything that happens in the canal network such as backfilling of canals, removal of control structure or changes of water control operations may be built into the model through they hydraulic model (MIKE11). Structural changes of, for instance, the geological layers of the groundwater model cannot be incorporated in the model. However, mining (if relevant) may be included also via the hydraulic model (if we are a bit creative).

Before attempting to built in structural changes that happens during the model calibration period it should be carefully considered whether this is a good idea or not. Sometimes it is better to understand the limitations of the model (for instance ability to calibrate local phenomena) than trying to incorporate details of local importance in the model. Hence, an inventory of changes to the system should definitely be developed before the model calibration is initiated. Subsequently, it should be evaluated if some of the activities in the basin should be included in the model.

Another option, which DHI has used a number of times, is to not include these structural changes during the calibration but use them as part of a model validation. Hence, if possible we may choose a calibration period without too many large changes to the system and then run a validation where a certain change has taken place. If the model can demonstrate the ability to simulate a regime that was structurally changed after the calibration then that is a very strong validation of the model.

8 CRITICAL TO THE IMPLEMENTATION OF THE MODEL IS THE ABILITY OF THE MODEL TO PROPERLY SIMULATE THE CONTROL FEATURES OF THE WATER CONTROL STRUCTURES. TYPICAL CONTROL FEATURES INCLUDE:

a. *The ability to include seasonal variation in regulation schedules*
b. *To limit maximum gate openings based on upstream and downstream water levels;*
c. *To simulate opening and closing rates of vertical lift gates,*

d. *The ability to hedge on structure discharge to meet recession rates on down stream reaches.*

Please discuss the ability of your model to effectively address these features.

Before describing how MIKE 11 will deal with the four mentioned control features an introduction to the control structure feature in MIKE 11 is given below.

The purpose of the control structure feature in MIKE 11 is to allow the user, as accurately as possible, to represent the control policies/rules/strategies that are actually applied, or are proposed for application, in real life. Across states, countries and continents control strategies are defined in a large number of different ways. Some are defined as dependent on season, some on weekday, water level, flow rate, rainfall, temperature, ground water level, level of water pollution etc. The structure operation module in MIKE 11 thus has many options, and generally is very flexible.

In MIKE 11, the complete set of rules that defines how to operate a gate, pump or reservoir release is called the control strategy. This is made up by a number of control definitions. Two things make up a control definition: 1) A number of conditions (logical expressions that are either true or false), and 2) How to operate the gate if all conditions are true. A very simple control strategy for a gate could be: If the water level downstream is higher than a certain value then close the gate; otherwise open the gate with a specified opening velocity. Another simple case is a pump for with two control definitions: 1) The pump runs, and 2) The pump does not run. The condition for the pump to run is that the water level is higher than the start level, or that the pump is already running and the water level is still higher than the stop level.

Conditions (logical expressions)
Each of the conditions, which the user can assign to a control definition, are defined as: How a value compares to a threshold. An example is: Water level downstream is higher than 10.7; i.e. the three components that make up a condition are:

Value: The choice of value could be something that MIKE 11 simulates, and there are 40 possible choices including water level, velocity, discharge, accumulated flow, volume in a reservoir. The location at which the value is picked can be any calculation point within the model. Values that are not simulated by MIKE 11 can also be referenced. This includes time related values such as year, month, week, day, hour etc.

Comparison: <, <=, >, >=, <> and = can be applied.

Threshold: A fixed or a time varying value can be given. For time varying values these are typically used to represent seasonally varying thresholds. The time variation is stored in a time series file as any other time dependent input.

How to operate the gate
Given that all conditions defined for a particular control definition are fulfilled we need to define how to operate the gate, i.e. MIKE 11 needs to know how to set the gate opening. There are the following choices:

Fully open: Open the gate to the maximum position as quickly as the max rate allows.
Close: Close the gate as quickly as the max rate allows.
Unchanged: Keep the gate opening unchanged.
Change with: Change the gate opening with a fixed value (positive or negative).

Set equal to: Set the gate opening to a fixed value.
Tabulated relation: A tabulated relation between the gate level and a so-called control value is specified. As for the *Value* used for the conditions the control value can be simulated variables (water level, discharge, velocity etc) or values related to time.
PID control: A classical use of PID control is to regulate a gate in order achieve a target water level upstream of the gate. The is achieved by the PID algorithm which, in the classical example mentioned, as a function of the difference between the actual water level and the target water level, suggests a change in the gate level; i.e. PID control is a gate level optimization feature. The PID control is working from one time step to the next such that the discrepancy between actual and target at one time step is resulting in a gate level change in the following time step. If the target changes a lot from one time step to the next, or if the upstream inflow in the mentioned example varies quickly, then PID is probably not the right choice. In such a case the iterative solution should be used.
Iterative solution: As for the PID control, the aim of the iterative solution is to achieve, as examples, a target water level upstream of the gate, or to ensure that the maximum flow downstream of the gate is not exceeded. Unlike the PID control, the iterative solution aims at reaching the target within each time step; i.e. the time step is iteratively repeated each time with a new gate level until the target is reached within limits.

As mentioned, several control definitions are typically applied for each gate. Each control definition is given a priority, and MIKE 11 goes through the list of control definitions in the order of descending priority and, for each time step, chooses the first control definition for which all conditions are fulfilled.

How MIKE 11 can deal with the four control features mentioned in the questionnaire is described in the following:

a. Seasonal variation in the regulation schedules can be included both by using time varying thresholds for the conditions, and by using time (month, week etc) related values for the conditions. In that way one control definition aiming at maintaining one reservoir water level could be applied during the wet season, and another control definition could be applied during the wet season.
b. Through a tabulated relationship between the upstream water level and the gate opening it would be possible to limit the maximum gate openings. Similar for the downstream water level.
c. For all gates the user needs to define the max rate (inches per minute for instance) at which the gate opening can change. Whenever a control definition dictates a particular change of the gate over a time step this will never be allowed to exceed the specified max change rate.
d. Depending on the exact formulation of the criteria either the tabulated, PID or iterative approach could be used.

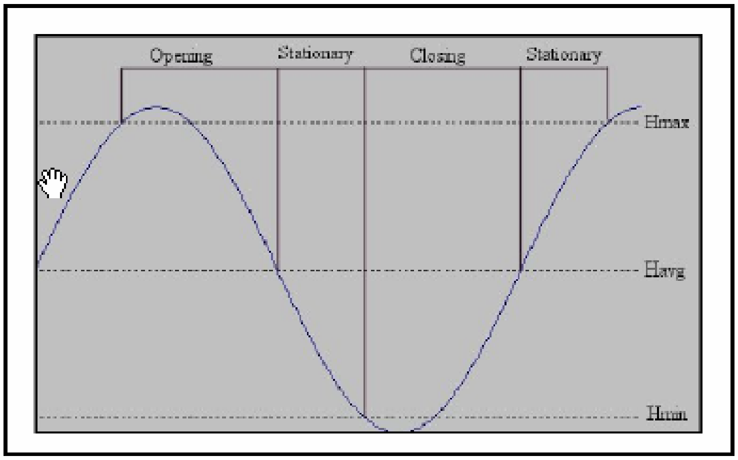


Figure 13 Example of a gate operation strategy used as part of the MIKE SHE model for Broward county.

9 OUR EVALUATION BOARD IS INTERESTED IN HOW YOUR MODEL APPROACHES THE MODELING OF SEASONALLY-FLOODED WETLANDS AND SINKHOLES FULLY CONTAINED WITHIN A MODEL CELL PLEASE PROVIDE A NARRATIVE STATEMENT EXPLAINING HOW THESE TWO FEATURES, COMMONLY FOUND IN SOME AREAS OF THE KB, WOULD BE SIMULATED BY YOUR MODEL.

There are different ways to represent these features in MIKE SHE. However, we believe that you should not always attempt to include small-scale features in a larger scale model unless these features are very important for the overall functioning of the system. It is DHI´s assessment that seasonally flooded wetlands less than the size of a cell size (eg 1000x1000 ft) are not important for the overall functioning of the system, but that sinkholes may be important for the overall water balance. Simple (hand) water balance calculations are typically sufficient to determine whether these features are important for the overall water budget or not and thus whether they should be considered in the model or not. If specific small wetlands are of interest for environmental reasons then it is recommended to establish local models using a finer grid size. Establishment of local model is seamless in MIKE SHE and can be done in short periods of time.

If however the small-scale features also prove to be important for the large-scale model, they may be included as follows:

Small wetlands will be implemented through the channel flow model. The channel flow model is grid independent and may contain small wetlands or lakes described either by cross-sections or by a relation between surface area and water depth (area-elevation curve). These small water bodies will interact with the overland flow, drains, and with groundwater as any other large channel or lake in the model.

Since the Floridan aquifer (most likely) is not considered directly in the KB model, then the sinkholes, from a modeling point of view, are just an export of water. The simplest way to deal with that would be to model them conceptually as isolated lakes in the hydraulic model. The lakes would be associated with a water level boundary condition representing the approximate piezometric head of the Floridan aquifer. Inflows to the lake would immediately leave the lake again through the open boundary. The sink-holes may exchange water both with overland flow and groundwater flow as appropriate. Including the lakes in the hydraulic model with not be a large effort and the lakes will represent only one calculation point and will be insignificant in terms of computational requirements.

10 PLEASE PROVIDE A DETAILED EXPLANATION OF HOW SUPPLEMENTAL AGRICULTURAL IRRIGATION/CROP WATER DEMANDS CAN BE HANDLED BY YOUR MODEL SPECIFICALLY, PLEASE DISCUSS THE ABILITY OF YOUR MODEL TO UTILIZE AN APPROACH CONSISTENT WITH AFSIRS (THE SFWMD PREFERRED CROP DEMAND TOOL).

MIKE SHE has an efficient and automated procedure for applying irrigation water. The automated procedure is based on a Maximum-Allowable-Deficit (MAD) approach where the user, in MIKE SHE´s vegetation database, specified the MAD. If the average water content in the root zone drops below the MAD, then irrigation water is added automatically by the irrigation module. The irrigation module was developed in co-operation with the SFWMD in 1996-1997 as part of the first MIKE SHE application and has since then been applied in all MIKE SHE models in South Florida.

User inputs are limited and simple. If it can be assumed that all irrigation command areas applies irrigation in the same way (drip irrigation) and that all irrigation water comes from the Floridan aquifer (external source - since the Floridan is not in the model) then the irrigation module only requires the inputs specified in Figure 14 - Figure 16.

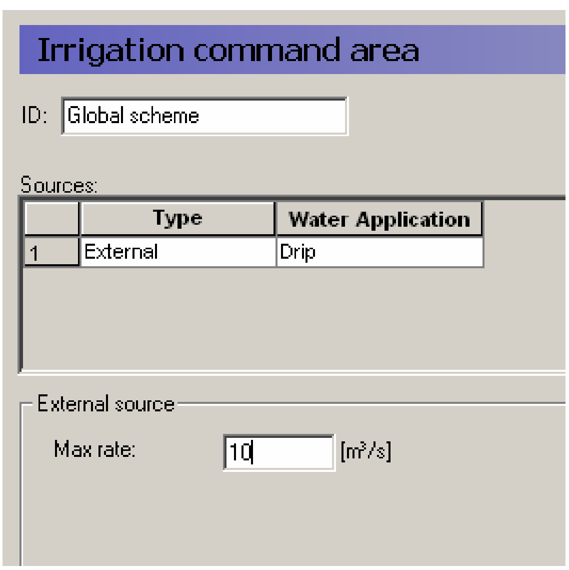


Figure 14 Specification of irrigation command area supplied by an external water source

The irrigation command area specification identifies the water source, in this case a water import, the application method (drip irrigation) and the maximum flow rate in the distribution system (in this case 10 m3/s).

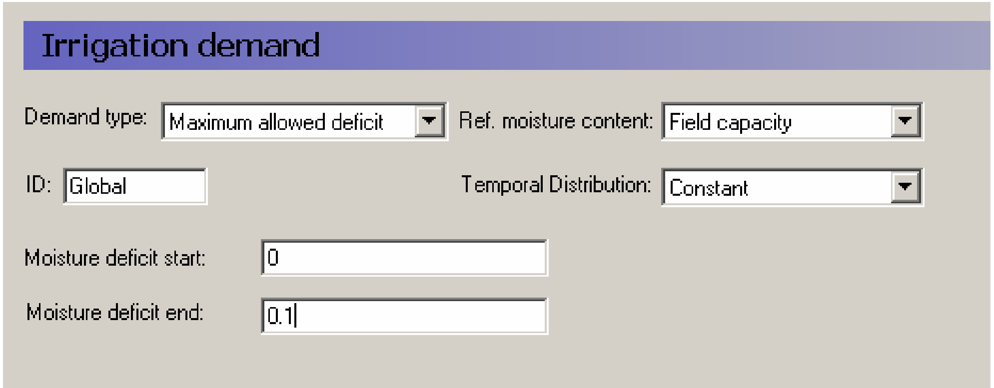


Figure 15 Specifications for Irrigation demand calculations using MAD

The irrigation demand specifications include the calculation method (MAD) and information on how irrigation demands should be calculated (soil moisture targets may vary in time) and finally the desired water regime to be maintained by the model. The moisture deficit start refers to the difference between Θfc and Θwp. In the above example irrigation will be applied if the average water content in the root zone drops below [Θfc - 0.1*(Θfc - Θwp)] and stops when the water content reaches Θfc (Ref. Moisture content).

Moisture deficit start and end may be specified by command area or by vegetation type. In the example above they are specified by command area.

Figure 17 shows an example of the simulated actual evapotranspiration in the Upper Kissimmee basin. Irrigated areas are recognized as distintly shaped areas with high evapotranspiration rates.

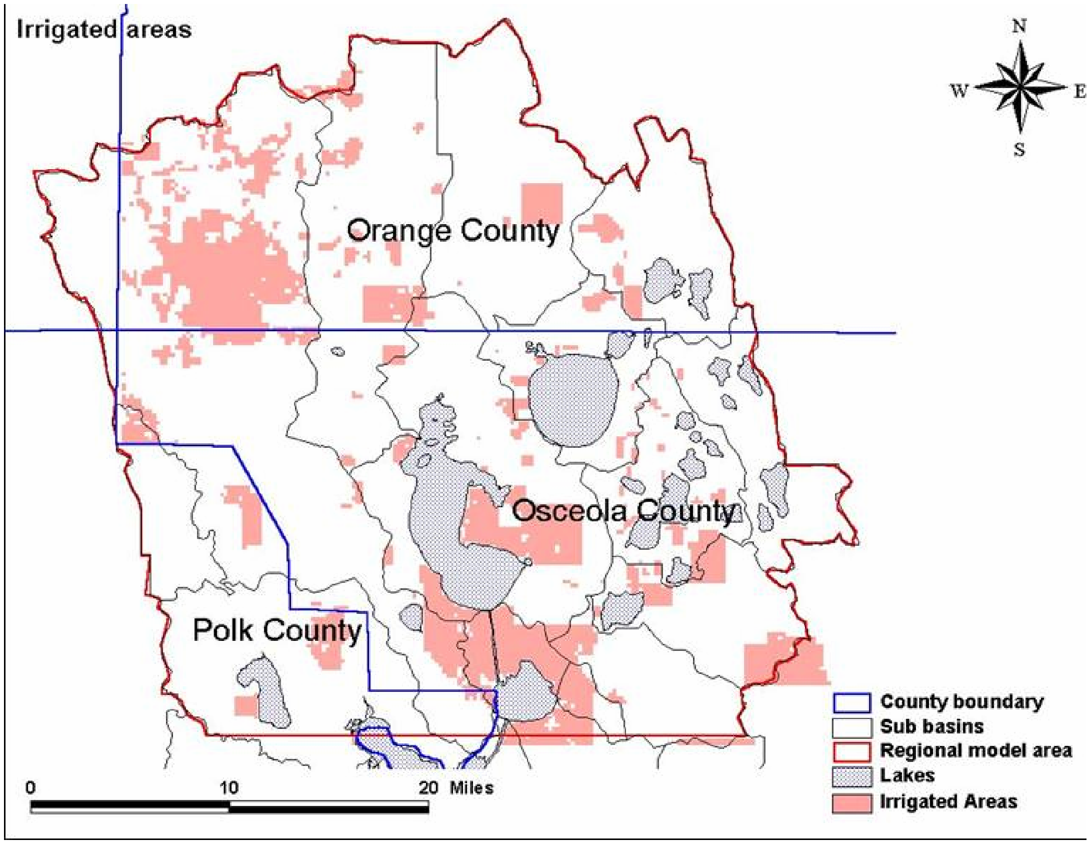


Figure 16 Map of irrigated areas

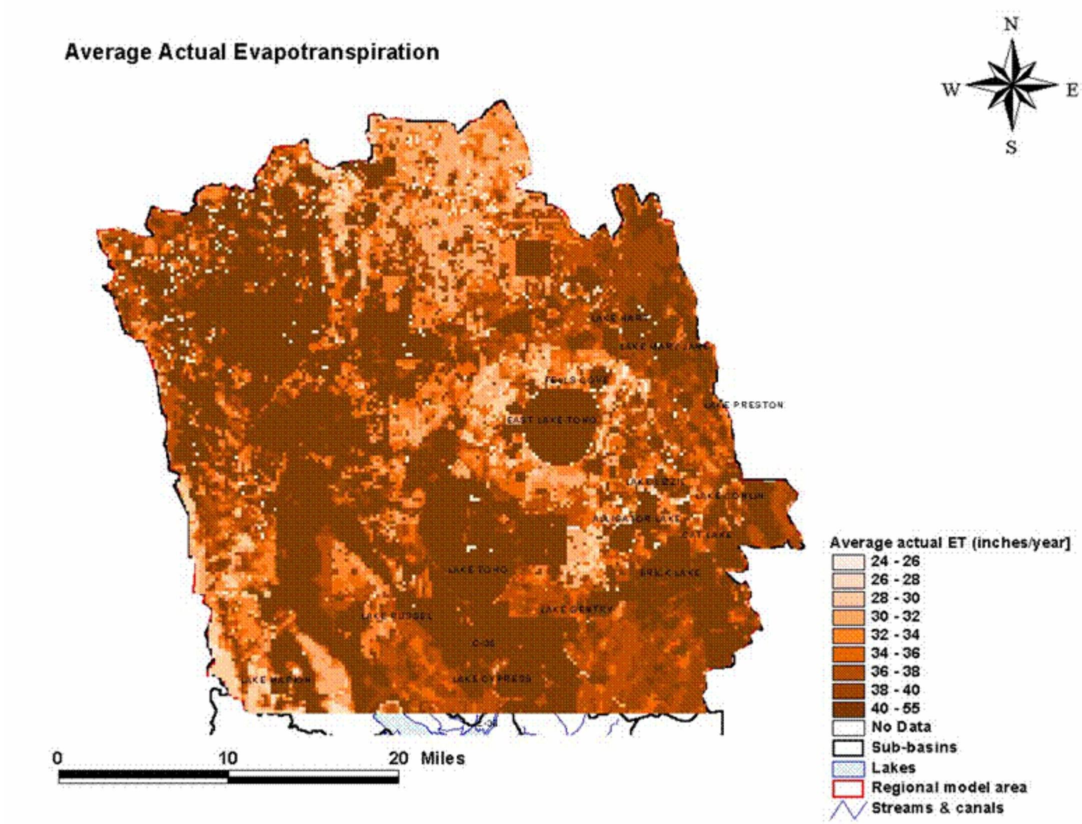


Figure 17 Calculated mean annual actual evapotranspiration in the Upper Kissimmee basin. Irrigated areas are recognized as distinctly shaped features with high evapotranspiration rates.

MIKE SHE irrigation approach is very similar to the approach used in AFSIRS. The basic assumptions in AFSIRS are the same as in MIKE SHE; namely that the sum of rainfall and irrigation water must be sufficient to meet the crops' ET requirements. As in MIKE SHE IR, AFSIRS also uses a root-zone water balance in combination with soil and vegetation properties to calculate irrigation demands. Similarly to MIKE SHE, irrigation water may be applied in different ways and AFSIRS may be run on daily, weekly or monthly time-steps. The two models appear to be very similar and consistent. Our AFSIRS review is based on a paper submitted by the University of Florida titled "Estimating Crop Irrigation Requirements for Irrigation System Design and Consumptive User Permitting" by A.G. Smajsgtrla and F.S. Zazueta.

11 PLEASE MENTION CAPABILITIES OF YOUR MODEL WITH RESPECT TO THE APPLICATION OF WATER THROUGH RAPID INFILTRATION BASINS, DRAINAGE WELLS, AND APPLICATION OF REUSE IRRIGATION WATER AND HOW IT IS SEPARATELY ACCOUNTED FOR IN THE WATER BUDGET COMPUTATIONS?

Rapid infiltration basins may be included easily as part of the hydraulic model (simple lakes) where they may interact with climate, groundwater and drains and with overland flow.

It is assumed that drainage wells are constructed wells that recharge the Floridan aquifer with surface water. In that case they will be treated similarly to sink-holes (see question 9).

The question on irrigation is not completely understood. MIKE SHE´s irrigation module allows for application of surface water or groundwater (or just imported water) to be applied as irrigation water using different water application methods (drip, sprinkler, flood irrigation). MIKE SHE does not describe operational losses in the irrigation canal system, unless these canals are included in the hydraulic model. If deemed necessary we can adjust the irrigation module so that it accounts for operational losses. MIKE SHE does account for situations where excess irrigation is applied and thus generates increased recharge.

Each of the above water fluxes will be treated as part of the water balance either as a water import or export if irrigation water is imported from outside the model domain (or from the Floridan aquifer assuming that the Floridan is not in the model). If irrigation water is taken from a canal/lake inside the model or from the surficial aquifer it will be treated by MIKE SHE as any other internal water flux. Outputs on water fluxes are easily retrieved and presented using MIKE SHE´s water balance program.

12 PLEASE PROVIDE A DESCRIPTION OF THE PROCESS USED BY YOUR MODEL TO SIMPLIFY THE SIMULATION OF FIELD DRAINS WITHIN EACH MODEL CELL, SUCH AS AGRICULTURAL DITCHES THAT ARE ABLE TO DRAIN THE WATER TABLE TO CHANNELS.

Most agricultural areas are naturally or artificially drained by creeks, ditches and tile drains. The purpose of these drainage features is to keep the groundwater level sufficiently low to allow for agricultural production. Runoff from drained areas often constitutes a substantial part of the total runoff from a basin and thus the ability to model the drainage features is essential. However, for large scale modeling you cannot include the drainage features in detail through the hydraulic model. MIKE SHE allows for a simple conceptual, but very efficient, way of including these important small-scale drainage features. The drains are essentially part of the groundwater model. In each cell the user may specify a drainage level or depth and time-constant for drain flow routing. Whenever the groundwater level is above the drains then drain flow is produced and routed to a channel or a lake or simply removed from the model (water export). Drain flow is calculated using a linear reservoir as:

U = dr0 * Cdrain, where U is the outflow rate of the linear reservoir [m/s], dr0 is the water heigh above the drains [m] and Cdrain is the time-constant [s^{-1}]. Each model grid contains only one drain (see Figure 18). The total outflow from a cell is thus calculated simply by multiplying with the area of a model grid. The runoff from a single cell is calculated simply by multiplying the outflow rate, U, with the area of the model grid.

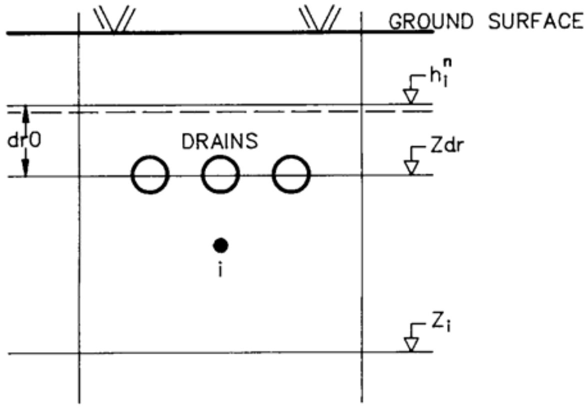


Figure 18 Subsurface drains in MIKE SHE

Thus the drain flow is calculated as described above. In addition the user must define where the water goes. MIKE SHE includes a number of automated options. The one that is usually most convenient is simply to specify drainage basins. Drain flow produced inside a certain basin will then always go to a channel/lake inside the same basin. MIKE SHE´s pre-processor will simply make a reference from each cell to the nearest river point inside the drainage basin. This approach was also used for the existing Upper Kissimmee MIKE SHE model as illustrated in Figure 19. For the upper Kissimmee model the watersheds for Reedy creek, Shingle creek etc. was used also for drainage basins. Hence, drain flow produced inside the Reedy creek basin would always drain to reedy creek.

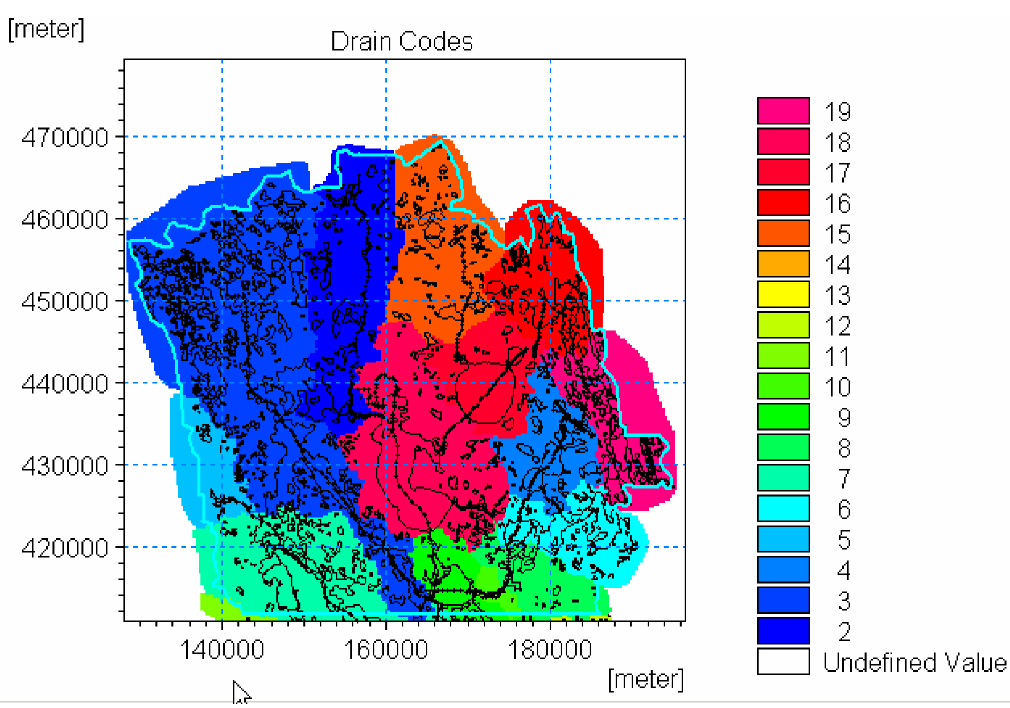


Figure 19 Drainage basins used in the upper Kissimmee MIKE SHE model. The integer code value is just an identifier for each of the drainage basins and may also be a text string (eg. the name of the basin).

13 IT IS EXPECTED THAT A SIGNIFICANT PART OF THE MODELING EFFORT WILL BE SPENT IN OPTIMIZING THE OPERATIONS OF COMPLEX STRUCTURE RULES APPLIED TO MULTIPLE WATER CONTROL UNITS IN THE KB. WE ANTICIPATE OPTIMIZING NUMEROUS VARIABLES, FOR MULTIPLE OBJECTIVES, FOR APPROXIMATELY 15 WATER CONTROL UNITS, INDIVIDUALLY AND AS A SYSTEM. THIS WILL BE ACCOMPLISHED BY PERFORMING SCREENING MODEL RUNS IN A DECOUPLED MODE (SCREENING MODEL OPTIMIZATION TOOL ACCESSES OUTPUT FROM MULTIPLE WATERSHED MODEL RUNS) AND IN A COUPLED MODEL (WHERE OPTIMIZATION TOOL SERVES AS A MANAGEMENT SIMULATION ENGINE TO THE WATERSHED MODEL). THE OPTIMIZATION TOOL HAS NOT YET BEEN SELECTED. PLEASE PROVIDE INFORMATION ON THE FOLLOWING:

a. A description of how your modeling tool can be applied to or support the screening functions described above.
b. If a third party optimization tool is selected, briefly describe the process and time-frame to prepare linkages for the simulations described above.
c. If you have an optimization tool available, please describe it’s capabilities to perform the simulations described above (provide examples).
d. The capability and feasibility to decouple the one-dimensional hydrodynamic routing to be used separately for performance measure optimization purposes.

13.1 Screening function and decoupling (question A and C)

Within MIKE SHE you may choose the simple lumped subsurface components (linear-reservoir routing) to generate inflows to the channel flow model (MIKE11 or alternatively MIKE BASIN or UKISS). The simple lumped models will most likely be able to produce reliable runoff estimates while they will not simulate groundwater stages and therefore cannot be used to predict impacts on, for instance, wetland hydro-periods. For screening level functions you may then de-couple hydrology and hydraulics under the assumption that changes of lake operation strategies will not significantly alter the total basin runoff (probably a reasonable assumption). However, if using MIKE11 for channel flow, it will still be a relatively time-demanding exercise where run times may be in the order of 10 minutes per simulation year if the entire basin should be simulated in one model. It will be fairly simple to make a model that only contains, for instance, the upper chain of lakes. An alternative to MIKE 11 is to use DHI´s MIKE BASIN model, which is a simple water balance based network model, or to use the existing UKISS model.

13.2 Optimization (question B and D)

DHI is currently using two optimization tools, AUTOCAL and OptiMIKE. Both would be applicable. Alternatively, third party options may be applied for instance using OpenMI interface standards (www.OpenMI.org). MIKE SHE, MIKE11 and MIKE BASIN are al OpenMI compliable and thus can be accessed via any other OpenMI compliable optimization tool.

DHI has used optimization on different projects. Most of them are related to optimization of reservoir rule curves in order to optimize flood protection and hydropower production. For the KB basin the optimization goals would be flood protection and environmental issues (downstream releases). However, essentially it is the same. DHI presently is conducting a research project where AUTOCAL was used to optimize rule curves on a large reservoir on the Red River in Vietnam (Hua Bin reservoir). This application proved to be very successful. The tool used in this application was MIKE 11, but other simpler tools such as MIKE BASIN or UKISS may be used as well.

Optimization is not always a straight forward case. For instance, if you want to optimize rule curves on all lakes together against a number of optimization targets, then a large number of model simulations may be required (500-1000 simulations). In practice that suggests a simpler approach such as MIKE BASIN and UKISS. The optimization could be evaluated using a so-called Pareto front approach where the goodness-of-fit for two objective functions (for instance flood protection and downstream releases) are plotted in a double scatter diagram. The Pareto front is a collection of the optimal solutions. It is however then up to the user to weight whether flooding (objective 1) should have a higher weight than downstream releases (objective 2).

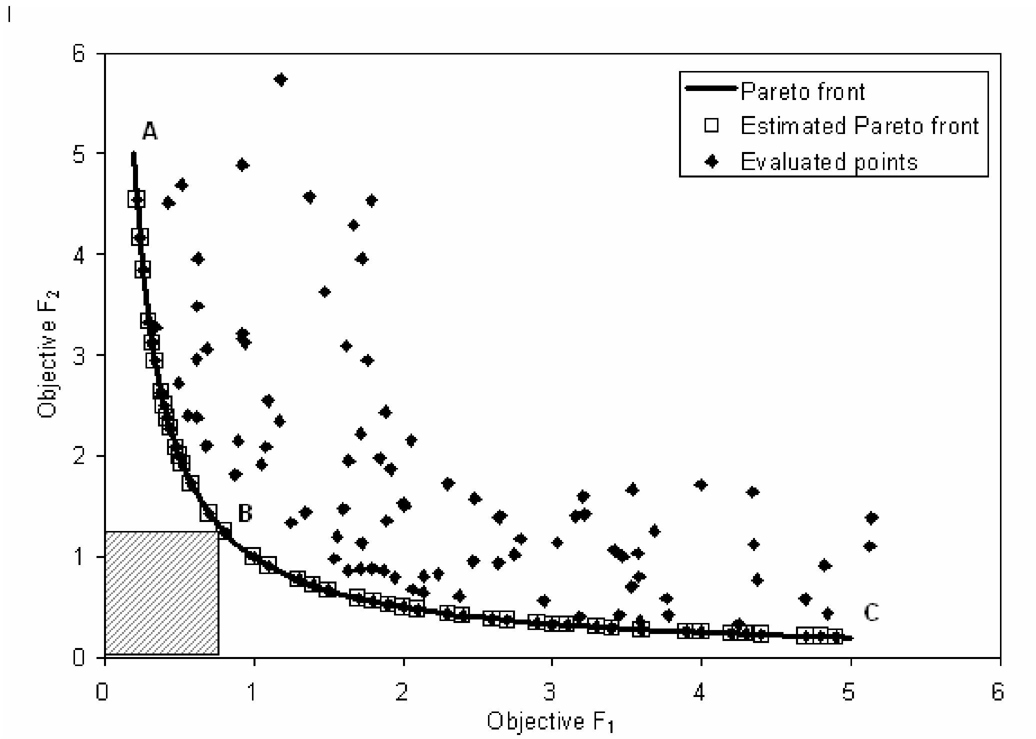


Figure 20 Example of Pareto front for two different objective functions (optimization targets).

Our suggestion would be initially to make a simple MIKE BASIN and MIKE11 model (for instance just one lake) to assess the feasibility of the two approaches and then subsequently choose which approach to choose for the final optimization problem and come up with an optimization strategy. In other words, we are not completely sure what approach would be best for the KB study but we know that we can find a feasible approach and provide an operational screening level tool suitable for optimization purposes.

14 PLEASE DESCRIBE YOUR MODEL'S WATER QUALITY MODELING CAPABILITIES, PARTICULARLY FOR TMDL ESTIMATION AND ANY EXPERIENCE WITH NPDES.

MIKE SHE offers various approaches for dealing with water quality issues that may be relevant for TMDL estimate. The "expensive" solution would be to run a physically based advection-dispersion model, which can be done for all components of the hydrological cycle in conjunction or for individual parts of the hydrological cycle (eg. groundwater only). However, an AD approach will be computationally intensive and calibration against field data (pollutant concentrations in surface water and groundwater) will be required. We suggest that a full AD approach would be overkill for the KB projects. We would instead suggest a much simpler approach where pollution loads (non-point and point sources) are estimated based on land-use, population density, animal farming etc. DHI has an ArcGIS based tool called LOAD that does this. LOAD then estimates pollution loads that may then go into the MIKE11 model. MIKE11 offers different ways of dealing with water quality through a very flexible component named ECOLAB which, in principle, supports whatever water quality process may be relevant (it allows the user to write his own process equations similar to the MATLAB concept). More information on the LOAD calculator and ECOLAB is attached as Appendix A.

15 PLEASE DISCUSS THE ABILITY OF YOUR HYDRODYNAMIC MODELING TOOL TO SIMULATE DRY OUT OR VERY LOW FLOWS IN THE ONE-DIMENSIONAL CHANNELS OR TWO-DIMENSIONAL GRIDS THAT MAY BE ENCOUNTERED AS PART OF THE EVALUATION OF PERFORMANCE MEASURES

Both MIKE11 and MIKE SHE´s overland flow model is able to deal with drying and wetting problems.

For the channel flow computations in MIKE 11, this problem is solved by allowing a so called "slot" below the cross-sections. The free water table is then computationally allowed to drop into the slot. The same equations are solved but in the numerical solution the coefficient matrix is manipulated (coefficients goes towards zero) to inhibit flows for dry or almost dry rivers.

On MIKE SHE´s overland flow the wetting and drying problem is resolved simply by using a threshold depth on the overland (eg. 0.1 mm) below which water does not move.

Hence, neither MIKE 11, nor the MIKE SHE overland flow module, have problems with drying and wetting.

An example of a seasonally flooded wetland in the Upper Kissimme model is illustrated in Figure 21.

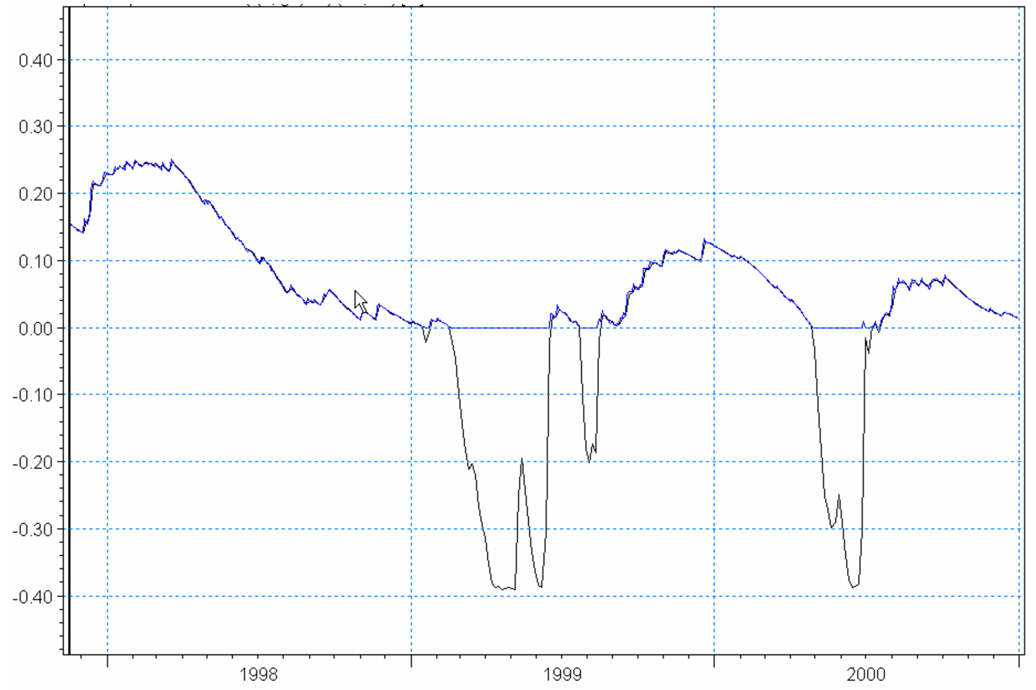


Figure 21 Example of a seasonally flooded wetland in the Upper Kissimmee basin. The blue line is the overland water depth and the black line is the groundwater depth. The wetland is flooded during most of the wet season but dries out during the dry season where the overland flow model is "dry". During the wet season overland water and groundwater are essentially at the same depth.

16 PLEASE PROVIDE A NARRATIVE OF SUCCESSFUL APPLICATION OF THE MODEL TO SIMILAR PROJECTS ALONG WITH METRICS ON OBSERVED AND SIMULATED DATA FROM A COMPLETED CALIBRATION/VERIFICATION EFFORT.

MIKE SHE has been used for numerous projects throughout the world. The bulk of the work has been done after MIKE SHE´s first official release in the early 1990´s. DHI´s project history currently contains 138 project references where MIKE SHE has been used. In addition, many MIKE SHE projects have been carried out by other consulting or research organizations. Hence, on total MIKE SHE has been applied on hundreds of integrated modeling projects since the early 1990´s.

16.1 Key International Projects

River Danube : 1992-1996, where MIKE SHE was used as the scientific backbone of a comprehensive modeling exercise related to the construction of a large hydropower plant (Gabcikovo) on the border between Hungary and Slovakia. In addition to regional modelling, MIKE SHE was also used to model sensitive riverine wetland systems along the Danube River. MIKE SHE modeling results played an important role in a legal dispute between Slovakia and Hungary resolved by the international court of justice. The link between MIKE11 and MIKE SHE was first developed and applied as part of this project

Kuala Langat National Forest, Malaysia, 2001-2002
MIKE SHE was applied to model the hydrology of a peat swamp forest south of Kuala Lumpur. Malaysia has built a new government city (from scratch) and placed it in the middle of a sensitive peat swamp forest. The construction of the city implies that parts of the swamp are drained resulting in loss of wetland habitat and increased risks of peat fires. MIKE SHE was used to study potential impacts of various plans for developing the city further into the peat swamp forest.

Okawanga delta water management plan (2004-2005)
MIKE SHE is currently being used as the hydrological simulation tool for a large water management plan for the Okawanga delta. The Okawanga delta is under pressure by different types of human activities as well as climate changes. MIKE SHE is used in similar manners as for many Florida studies, to study various development scenarios with focus on meeting water demands in the area as well as environmental targets (hydro-period). The first phase of the MIKE SHE modeling has been concluded and a calibrated MIKE SHE model is now available.

16.2 Projects in Florida

MIKE SHE has been used at many locations in South Florida since the first MIKE SHE application in 1996 (modeling the hydrology of an ENR site). Figure 22
shows areas in South Florida where MIKE SHE has been applied. As part of the many MIKE SHE applications in South Florida, the MIKE SHE model has been "tuned" to meet District requirements. For instance the two-layer unsaturated zone model and MIKE SHE´s irrigation module were developed in cooperation with the SFWMD.

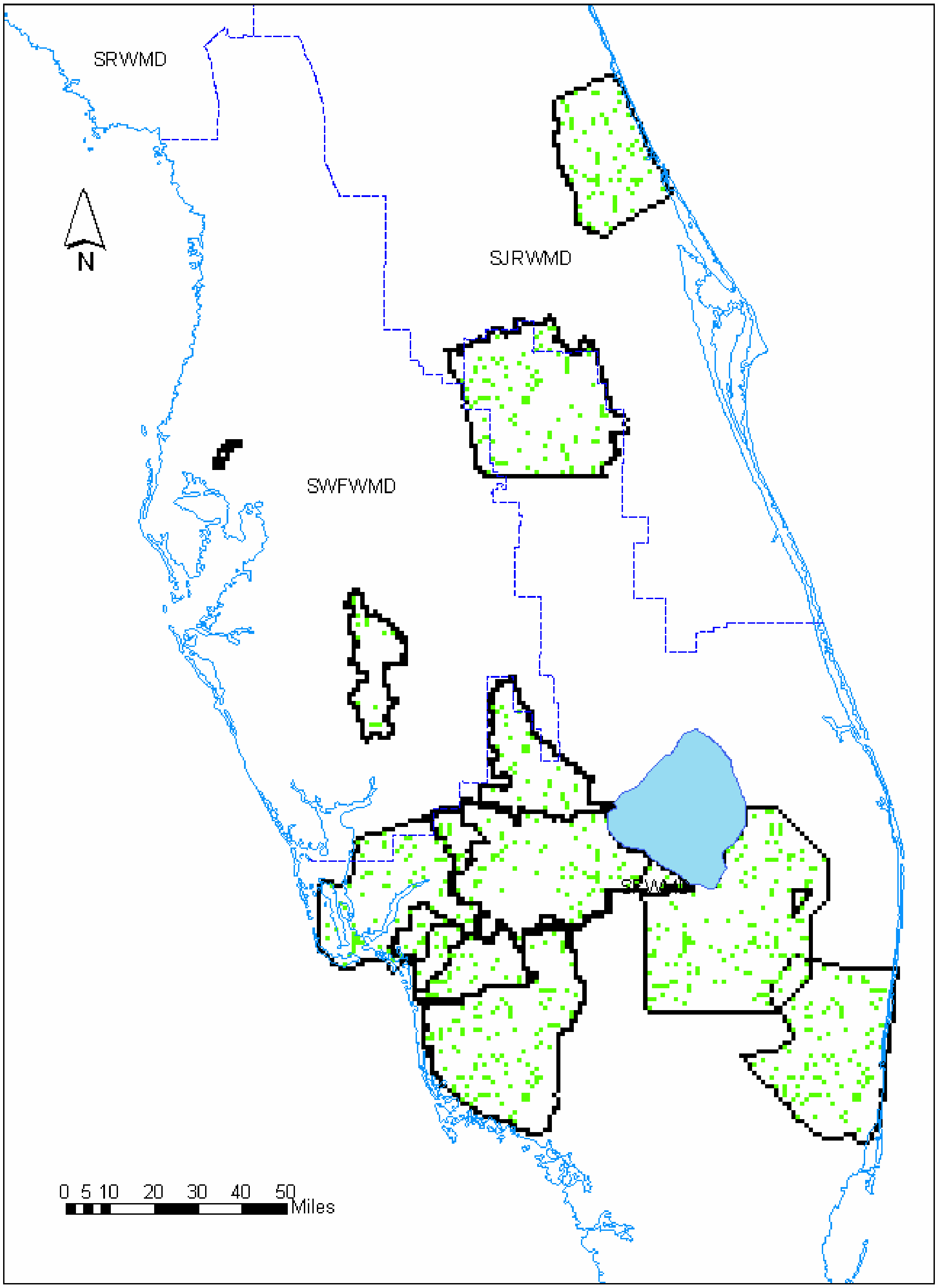


Figure 22 Overview of MIKE SHE modeling areas in South Florida.

16.3 Examples of MIKE SHE performance measures (calibration)

16.3.1 Broward County Model in South Florida

The Broward county model is characterized by urban activities and runoff, large amounts of groundwater pumping and extreme interactions between surface water and groundwater. The following includes sample calibration statistics for the Broward county model. In general the Broward county model is very well calibrated with average mean absolute mean errors well below one foot. In any model calibration there are observations that cannot be matched by the model. For the Broward county model there was one well in particular where the model is obviously not able to simulate the behavior of the system. Usually such obvious deviations are due to operations in the basin that are not included in the model. In this case we were not able to identify the reason. Moreover, the problematic well was not located in the main area of interest. To illustrate the quality of the model calibration hydrographs representing worst case, typical and best case calibrations are illustrated.

The model also reproduces surface water stages and runoff with good precision. However, simulation of runoff is a difficult task in South Florida because rainfall events are local and intense. During the dry season it is particularly difficult because the gates essentially remain closed. Hence, there are no surface water outlets. Simulation of stages in canals thus becomes entirely a function of the rainfall, the actual evapotranspiration, the storage in canals and lakes, and the groundwater-surface water exchange flows. Not easy at all, but the Broward model does a fair job even during the dry season. During the dry season of 1989-1990 the simulated water table drops way below the observed. In the rainfall data used by the model there is essentially no rainfall during that period. Nevertheless, the observed water stages are still staying relatively high and even increasing in periods with no rainfall data. This is either due to poor rainfall data or flaws in support inflows to the Broward canal system from the surrounding WCA´s.

	Observed Data			BC ISGM		BC MODFLOW	
Well ID	No. of obs.	min (ft)	max (ft)	Mean Absolute Error (ft)	Frequency within 1 ft (%)	Standard Error (ft)	frequency within 1 ft (%)
G-2443	1069	0.5	6.0	0.4	91	0.7	85
G-2444	1092	4.5	8.8	0.5	90	1.7	37
G-2122	38	0.6	3.7	0.6	81	N/A	N/A
G-2130	39	0.6	2.6	0.7	69	N/A	N/A
G-1343	36	1.0	3.7	1.3	25	N/A	N/A
G-561	1068	0.7	5.1	0.3	96	0.7	87
G-1220	1093	0.5	4.5	0.5	85	N/A	N/A
S-329	1064	-0.8	6.1	0.9	62	1.3	51
G-2032	1092	3.2	6.4	0.5	88	0.7	87
G-2033	1093	5.2	8.8	1.8	31	0.62	92
G-2395	882	-13.7	-4.2	1.2	46	N/A	N/A
G-820A	1093	1.9	7.5	1.7	18	1.3	58
G-1262	761	-10.9	-6.0	1.6	34	N/A	N/A
G-1344	29	0.8	3.2	0.7	79	N/A	N/A

Green cells indicate BCISGM model provides better calibration results
Yellow cells indicate BC MODFLOW model provides better calibration results
G-2443, G-2444, and G-1262 were used for the Study Area Model calibration only

Figure 23 Overall performance statistics for MIKE SHE and existing MODFLOW model.

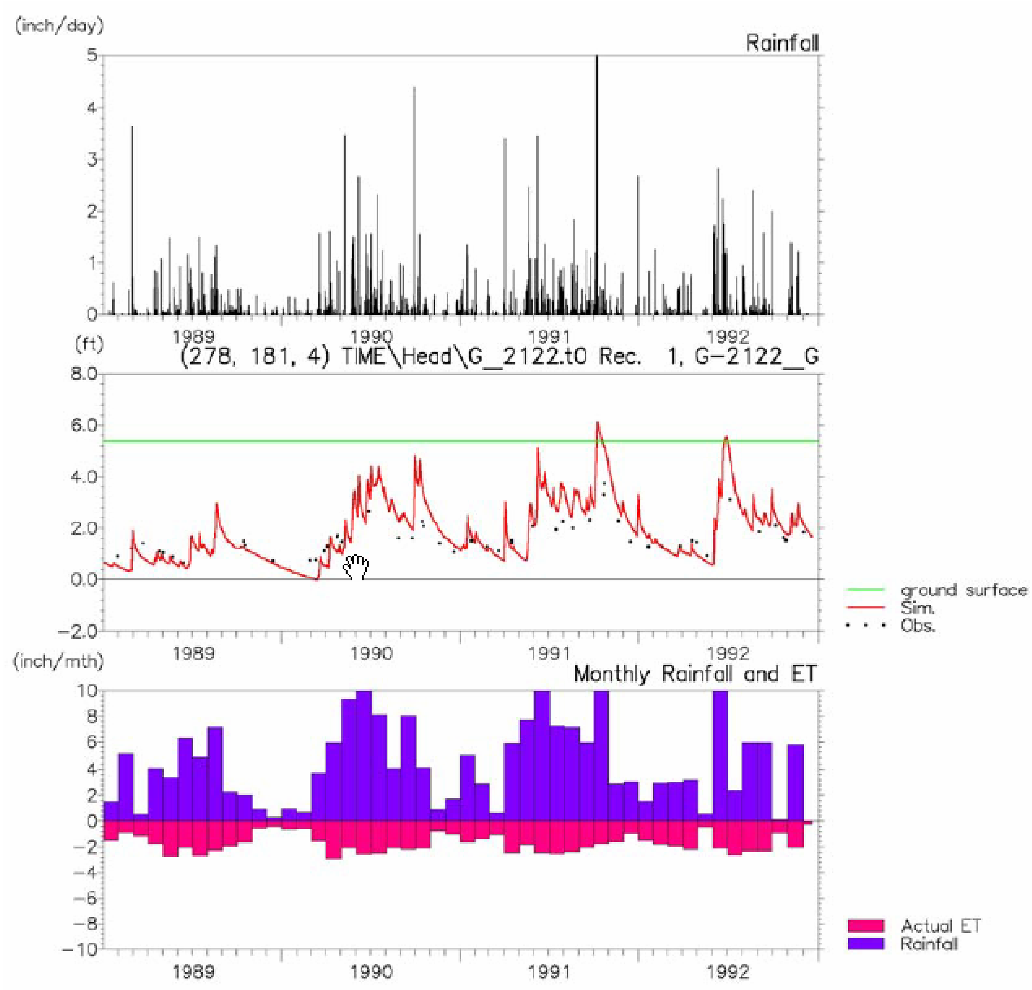


Figure 24 Typical calibration hydrograph (groundwater) for the Broward County model

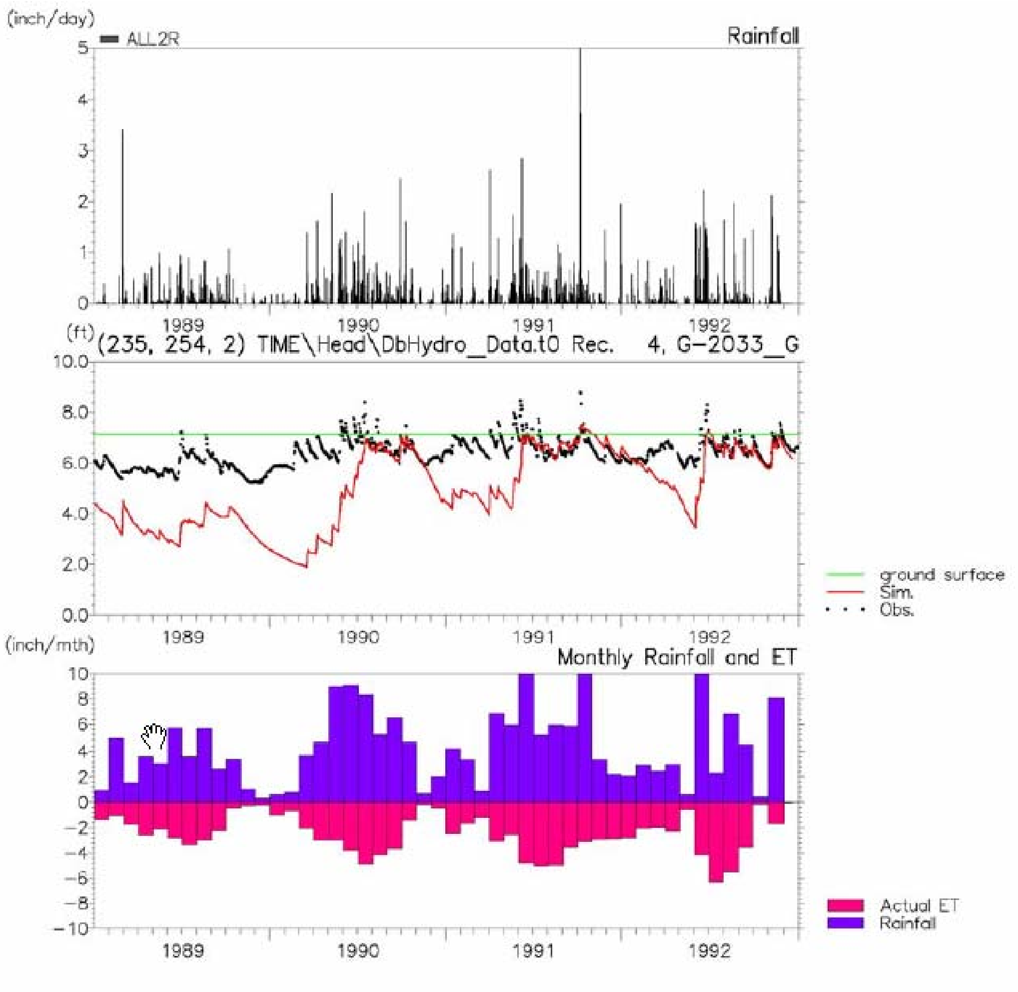


Figure 25 The worst groundwater calibration hydrograph (G-2033)

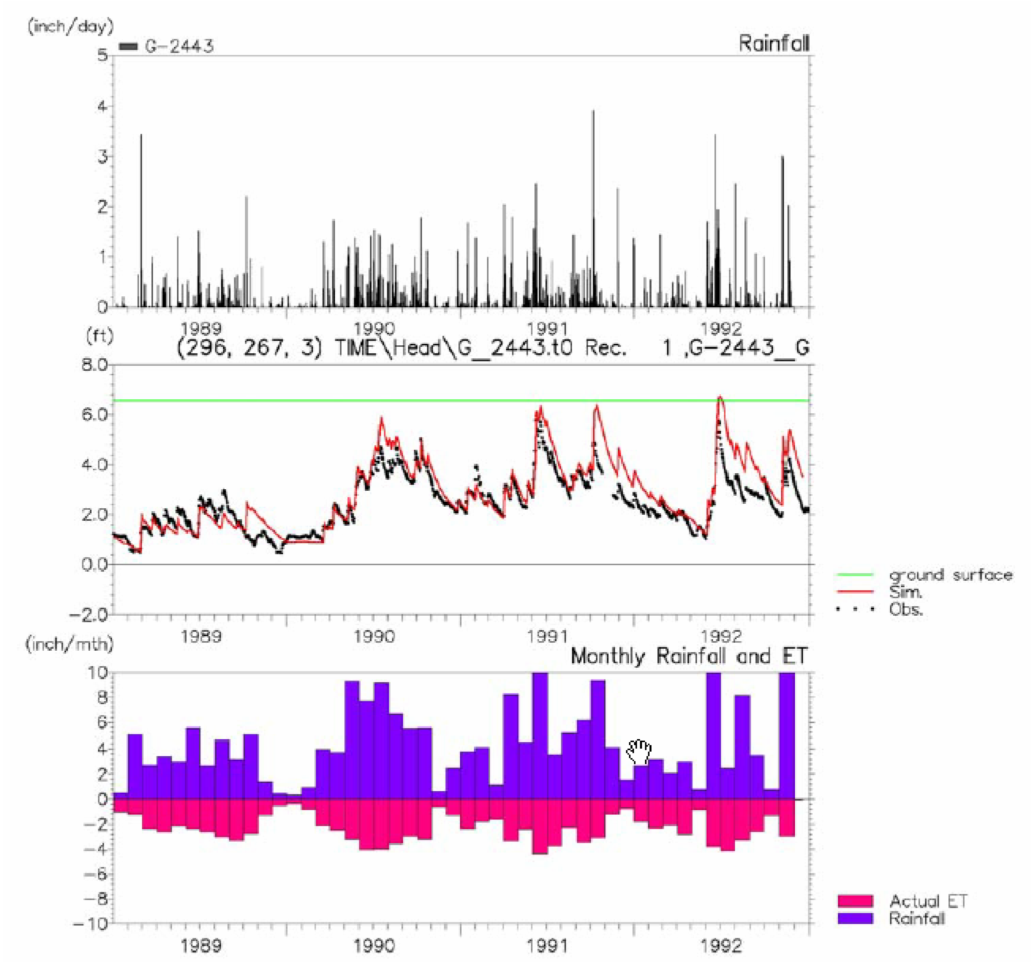


Figure 26 The best groundwater calibration hydrograph (G-2443)

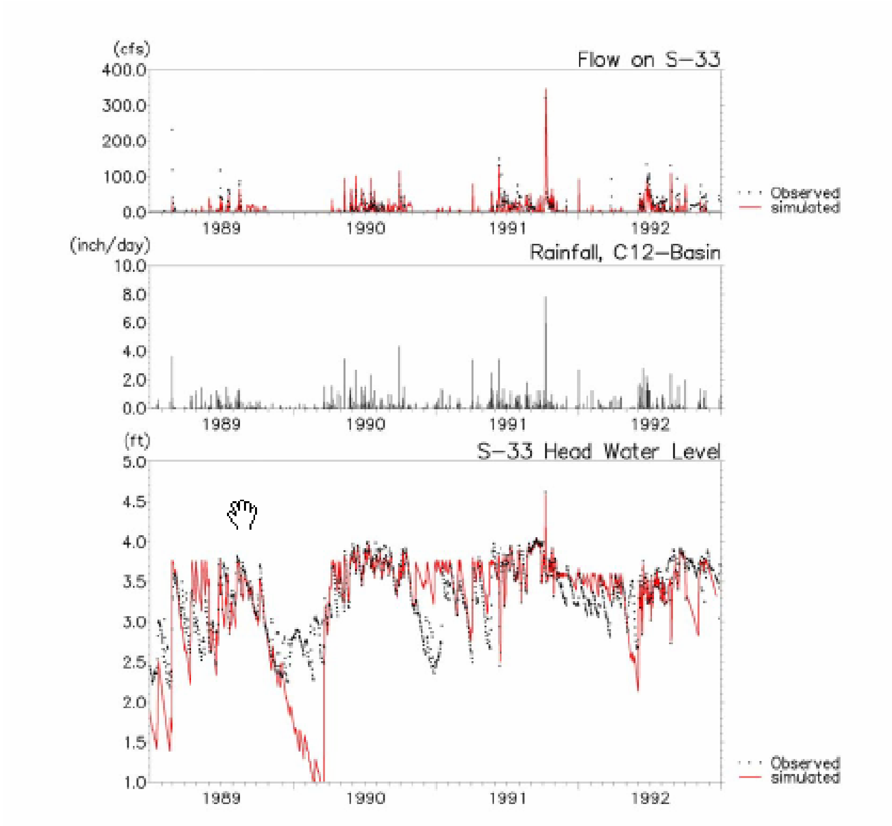


Figure 27 Surface water flows and stages at S-33 during the wet season of 1991.

16.4 Calibration outputs for the existing MIKE SHE model of the upper Kissimmee basin.

The graphics below illustrates the quality of the calibration outputs of the existing Upper Kissimmee MIKE SHE model. In general the model is able to simulate observations with a precision about 1 foot or less. As always, there are however, a couple of wells that fall substantially outside these limits. For instance Beeline_G (see Figure 32) is 2.7 feet off on average. Simulated dynamics appears to be ok, but the simulated levels are consistently too low. A reason for this discrepancy was not identified or pursued with large enthusiasm since the well was located well away from Lake Toho which was the main area of interest. It does appear likely that there are datum errors in the observed water levels or in the topographic data at that location. According to the observations the water stage at that location is above ground surface for a great period of time. The dynamics of the observation however looks more like a groundwater level than a surface water level.

Number	Well identification	Observed Data			Simulation Statistics				
		No. of observations	Min (ft)	Max (ft)	Mean absolute residual (feet)	% of obs. within target			
						R1	R2	R3	R4
1	Simmons #1	1047	67.0	73.6	1.0	100	74	86	90
2	Simmons #2, well 1	1041	63.4	69.9	0.4	100	98	99	100
3	Simmons #2, well 2	1047	63.4	69.8	0.4	100	98	98	100
4	Beekman	963	61.9	66.9	1.7	100	15	62	73
5	Exotic	965	67.7	70.8	0.8	100	47	78	92
6	Toho 10	556	65.5	70.5	0.5	100	92	95	100
7	Toho 12	225	66.8	69.8	1.0	100	62	66	78
8	Toho 13	234	57.5	60.9	2.7	99	1	39	27
9	Toho 15	548	69.6	75.2	2.0	100	10	69	47
10	Toho 16	571	63.6	67.2	0.8	100	36	94	99
11	Toho 1	632	56.9	62.0	0.2	100	100	100	100
12	Toho 2	556	58.4	64.3	2.0	100	31	67	63
13	Toho 3	185	53.6	58.2	0.8	100	85	100	99
14	Toho 5	215	63.5	68.3	0.9	100	92	87	100
15	Toho 4	231	54.7	59.8	0.6	100	87	98	98
16	Toho 6	226	60.8	65.9	0.6	100	84	100	91
17	Toho 8	41	59.6	60.6	2.9	0	0	0	15
18	Toho 7	159	65.2	67.4	1.1	98	8	52	87
19	Toho 9	223	68.1	71.9	1.0	100	66	62	77
20	Taft	937	92.5	97.2	1.8	100	6	42	72
21	Sunset	964	59.0	65.4	0.8	100	86	100	98
22	Pine Island	961	73.7	79.2	0.8	100	63	95	99
23	OS-181	823	71.7	78.5	0.6	100	89	100	93
24	Moonlight #2 well 2	1042	65.5	70.3	0.7	100	69	97	100
25	Moonlight #2 well 1	1054	65.5	70.5	0.7	100	70	98	100
26	Moonlight #1 well 1	1055	66.6	72.4	0.8	100	76	81	95
27	Moonlight #1 well 2	1055	66.6	72.2	0.8	100	77	81	95
28	Mako	1046	71.2	76.3	1.3	100	40	81	79
29	Kiss.FS2	981	65.7	71.3	0.8	100	77	99	94
30	Disney	939	94.3	99.2	0.7	100	88	99	96
31	Chestnut, well 1	1024	63.4	72.2	0.7	100	87	100	90
32	Chestnut, well 2	966	63.4	72.1	0.8	100	87	100	90
33	Castell, well 1	1054	67.2	71.2	1.9	100	13	61	63
34	Castell, well 2	1049	66.7	70.6	1.1	100	47	99	86
35	Blackwater	1048	67.5	71.9	0.8	100	59	78	100
36	Beeline_g	899	81.6	86.9	2.8	100	1	33	13
Average residual and no. of wells meeting 75% criteria					1.1	35	15	24	28

Figure 28 Overview of groundwater calibration statistics for the Upper Kissimmee MIKE SHE model.

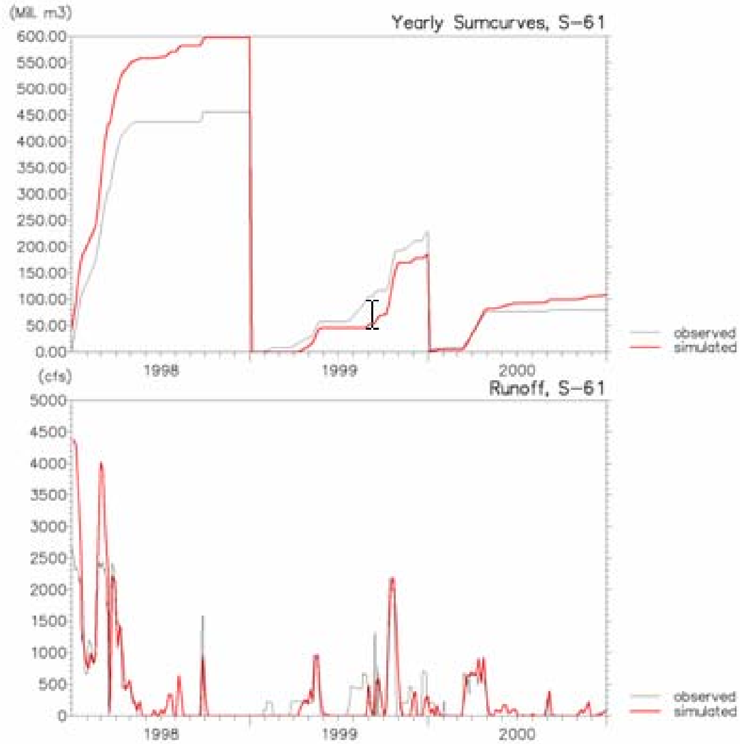


Figure 29 Simulated and observed runoff at S-61

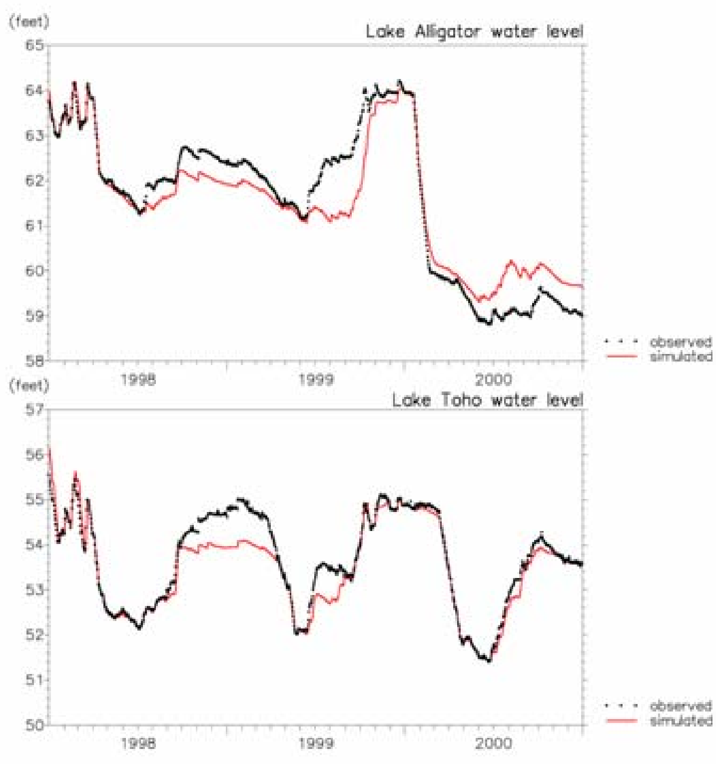


Figure 30 Simulated and observed water level in Lake Toho.

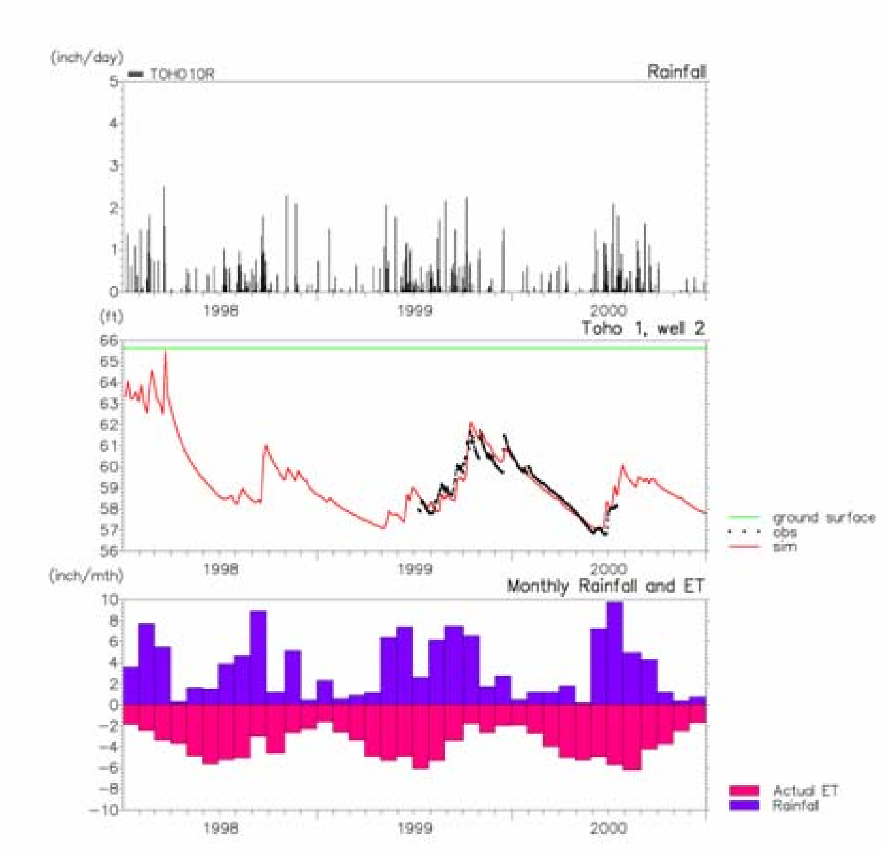


Figure 31 Simulated and Observed groundwater level at piezometer Toho 1 (best calibration)

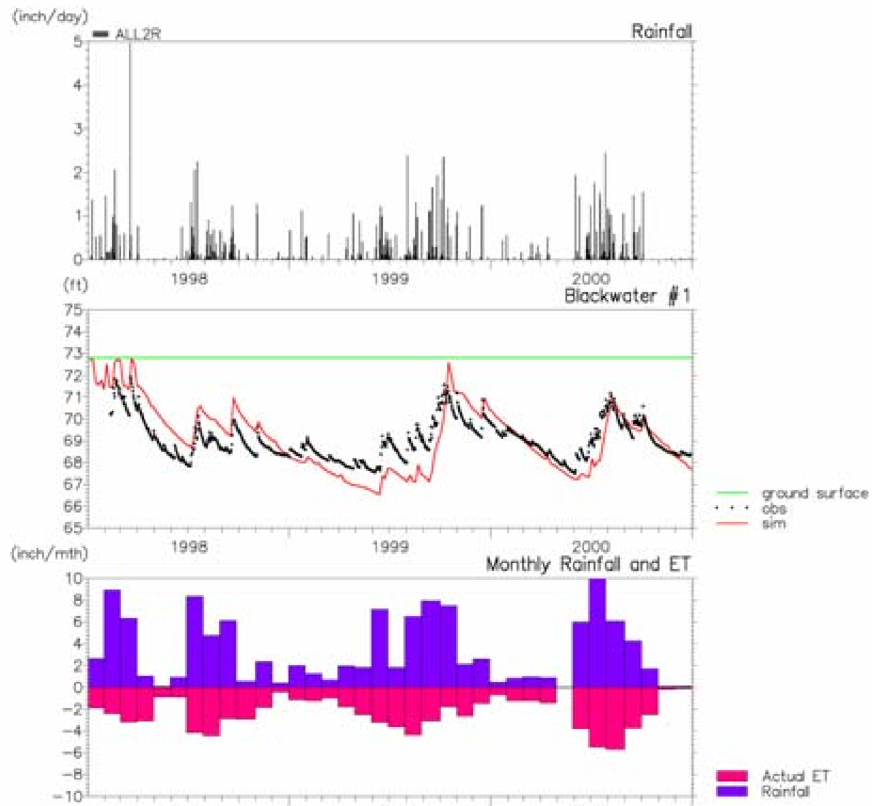


Figure 32 Simulated and observed groundwater level at Blackwater (typical groundwater calibration quality).

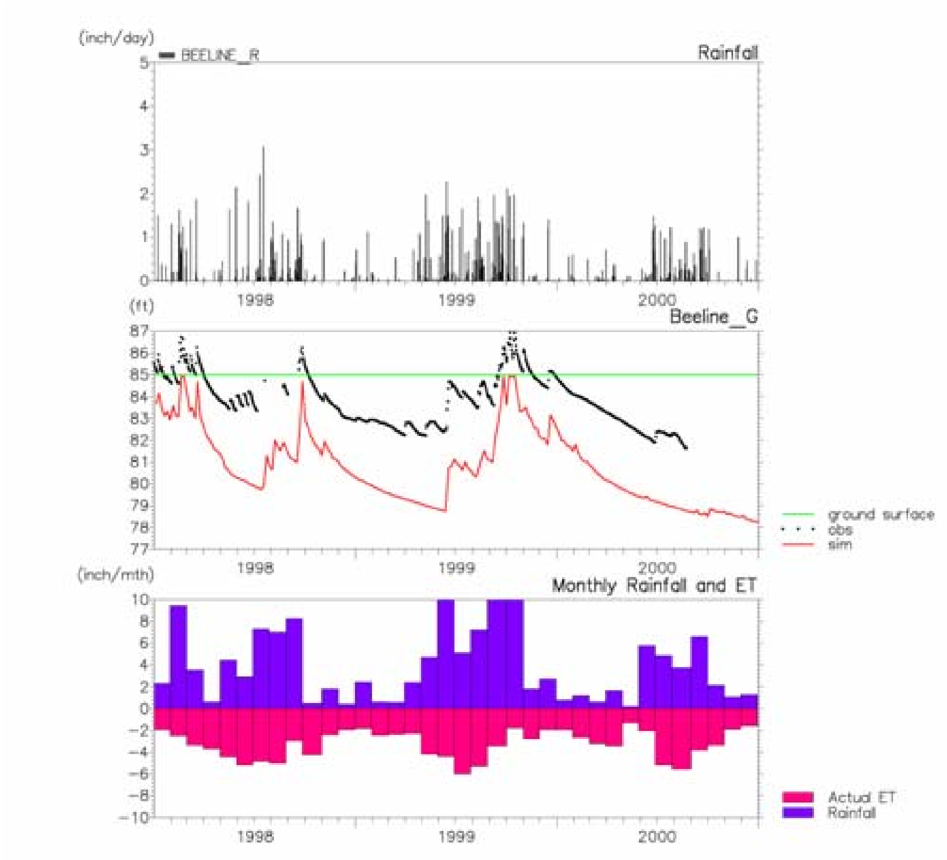


Figure 33 Simulated and observed groundwater level at piezometer Beeline_G (worst case simulation).

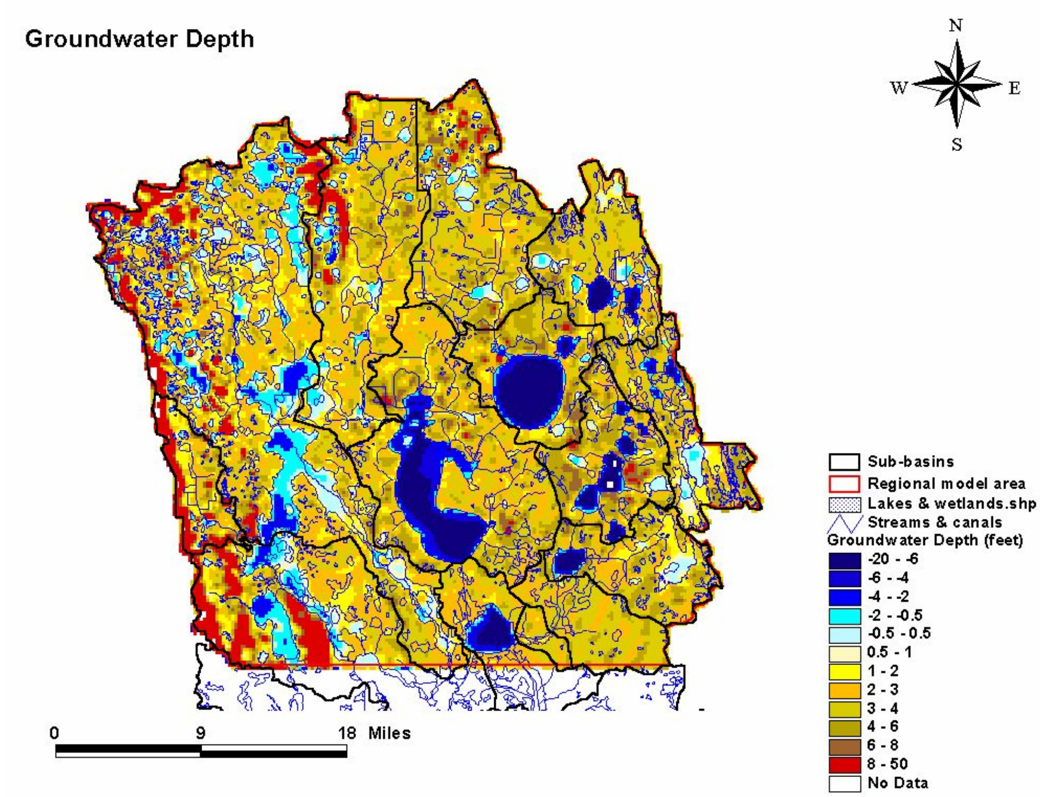


Figure 34 Sample outputs - average depth to water table. Negative values indicate water above ground surface.

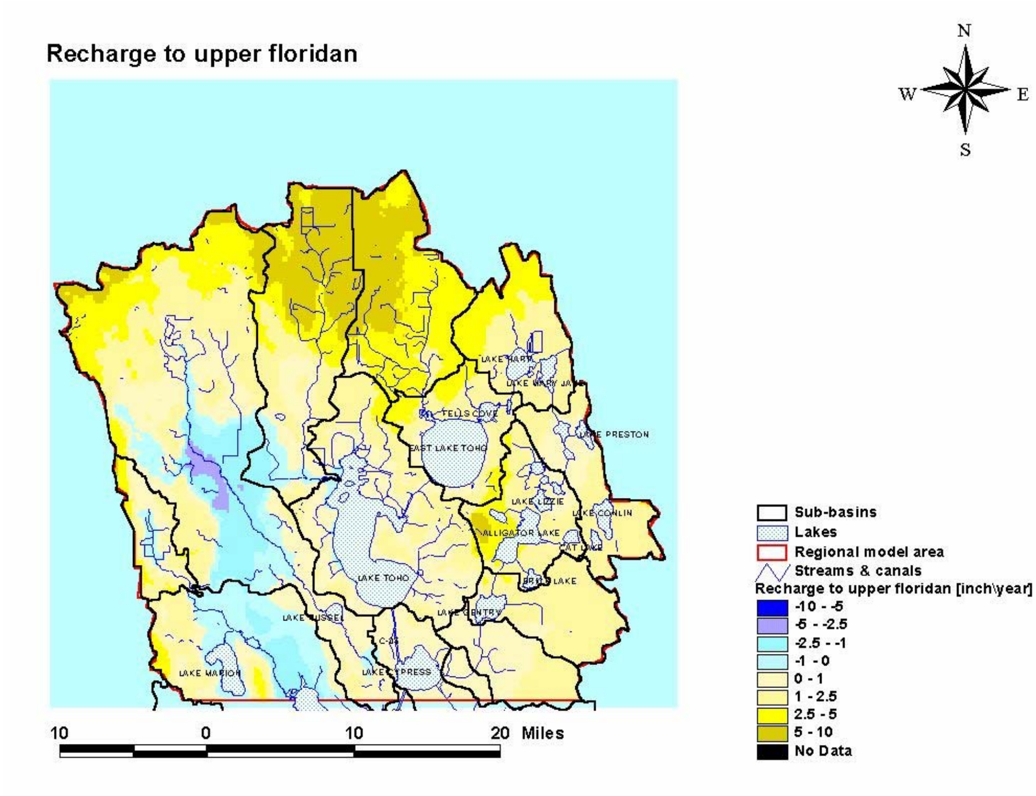


Figure 35 Sample outputs - simulated recharge to the Floridan aquifer

16.5 Defensibility

MIKE SHE has been reviewed in various connections. Review documents are available on WWW. MIKESHE.COM.

MIKE SHE have been involved in court cases three times in Florida in connection with the Lake Alligator and the Lake Toho drawdown studies and in connection with a recent court-case involving permitting for phosphate mining in the Peace river basin (Horse Creek model). In all cases MIKE SHE was on the "winning team".

MIKE SHE studies have been published in numerous scientific journals. Appendix B (Flexible Integrated watershed modelling with MIKE SHE) contains a comprehensive list of MIKE SHE references. In addition to this, MIKE SHE models have appeared in numerous conference proceedings.